PSMC

1 Parts Standardization & Management Committee (PSMC) Spring Conference

McLean, VA

April 20-22, 2010

Recently…

In the last several weeks several briefings to present the case for

Manhattan phase 3 now PERR…occurred.

These slides were presented by LM, and several Manhattan SME's in multiple sessions to several people including DoD,, Director Research & Engineering, ONR, Director of Transition and Director of Research

This effort continues with assessment and planning at the center of discussion and dialog…..

Today…

- Pb-free Electronics Risks & Failures
  - Tin Whiskers
  - Issues with Pb-free Alloys in COTS Electronics
  - Unpredictable Service Life & Reliability for the Warfighter

- Risk Reduction Strategy
  - Pb-free Electronics Risk Management (PERM) Consortium
  - "Manhattan Project" to Scope the Problem
  - Pb-free Electronics Risk Reduction Program
    - Determine the True Physics of Failure for Pb-free Electronics
    - Quantify the Reliability for the Pb-free COTS Replacements
    - Characterize the Preferred Replacements and How They Perform
- Program Funding & Execution
- Pb-free Electronics Risk Reduction Details
- Pb-free Electronics Risks Technical Discussion…

Pb-free Electronics Risks & Mitigation

Aerospace Industries Association

Aerospace and Defense: The Strength to Lift America

NDIA

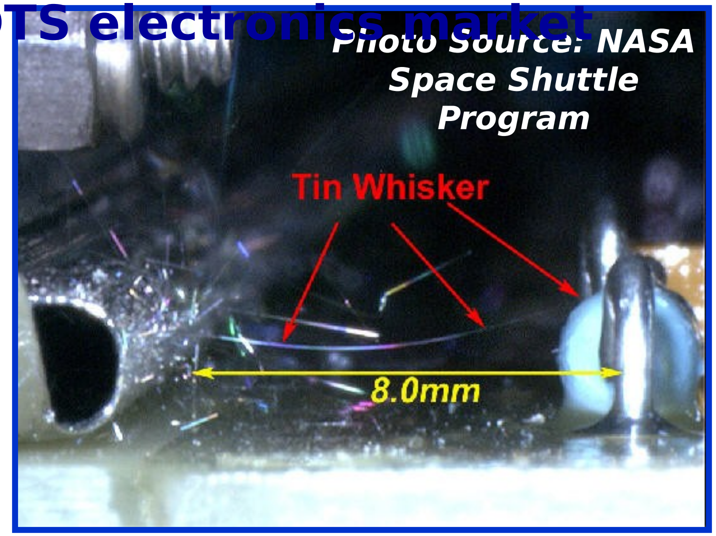
National Defense Industrial Association

Promoting National Security Since 1919

3/26/10

Pb-free Electronics Risks

EU Restriction of Hazardous Substances (RoHS) Directive banned use of lead (Pb) in commercial electronics sold in EU as of 7/1/06, impacting global COTS electronics market



Unintended Consequences

- **"Tin Whisker" Short Circuits**
  - Electrically conductive
  - Can metal vapor arc
- **Pb-free Solder Issues**
  - Fractures in high shock & vibration environments
  - Has higher melting temps
  - Incompatibilities with SnPb Solder
  - Less repairable assemblies
- **Configuration Control Nightmare!**
  - Unidentified component alloys
  - Mixed Pb & Pb-free inventory

Electromagnetic Relay Vapor Arc Damage

Pb-Free Solder Joint

Have Tin Whiskers Caused Failures?

- **Multiple Documented Occurrences (NASA/Industry/Academic Publications)**
  - **Nuclear Utilities**
  - **7 Satellites ($100M Boeing Loss)**
  - **Patriot (PAC-2)**
  - **6 Missile Programs**
  - **Heart Pacemaker**
  - **F-15 Radar**
  - **Military Airplane**
  - **Telecom. Equip.**
  - **Heart Defibrillators**
  - **New Commercial Autos**

$1B Worth of Satellites, Missiles & Other Equipment

Catastrophic Damage Due to Tin Whisker Induced Metal Vapor Arc

NOTE: Electromagnetic Relay Was Purchased to MIL Spec Prohibiting Pure Tin Finish Inside, But IT WAS Pure Tin

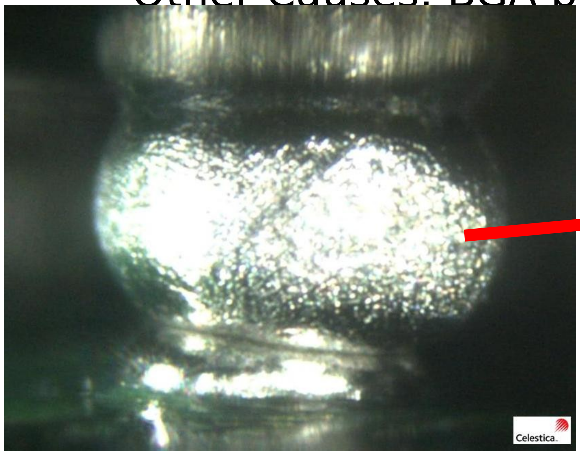
Ref: http://nepp.nasa.gov/whisker/failures/index.htm

Recent Pb-free Electronics Failures

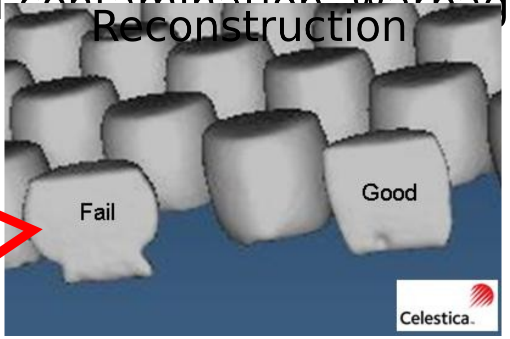
SAC BGA Rework "Head in Pillow (HiP)" Defect – Manufacturing Issue

- Problem: <u>Intermittent</u> ATC open failure after rework (2000 I/O BGA with 1 open joint)
- Lab Analysis: Metallurgical analysis found "head-in-pillow" and differential cooling between balls and paste
- Corrective Action: SAC process requires regular calibration of reflow heaters
- Other Causes: BGA ball contamination, warpage

BGA Ball Open (HiP)

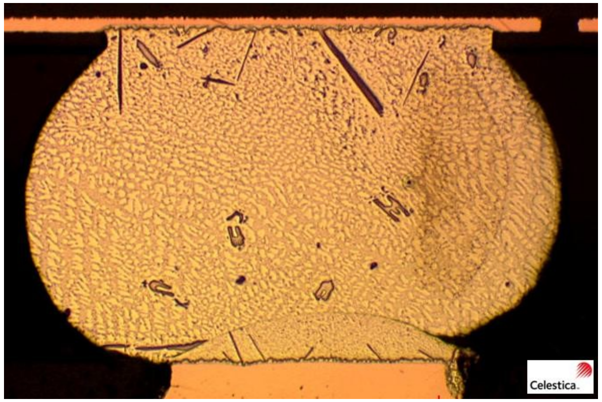


3D X-ray Reconstruction

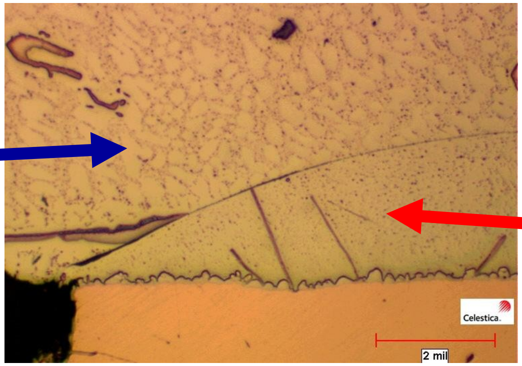


Photos Provided by Celestica

Paste & SAC Ball Not Wetted



Large Sn Dendrite Indicates Slower Cooling at Component Side



SAC Paste Resolidified Before Wetting to BGA

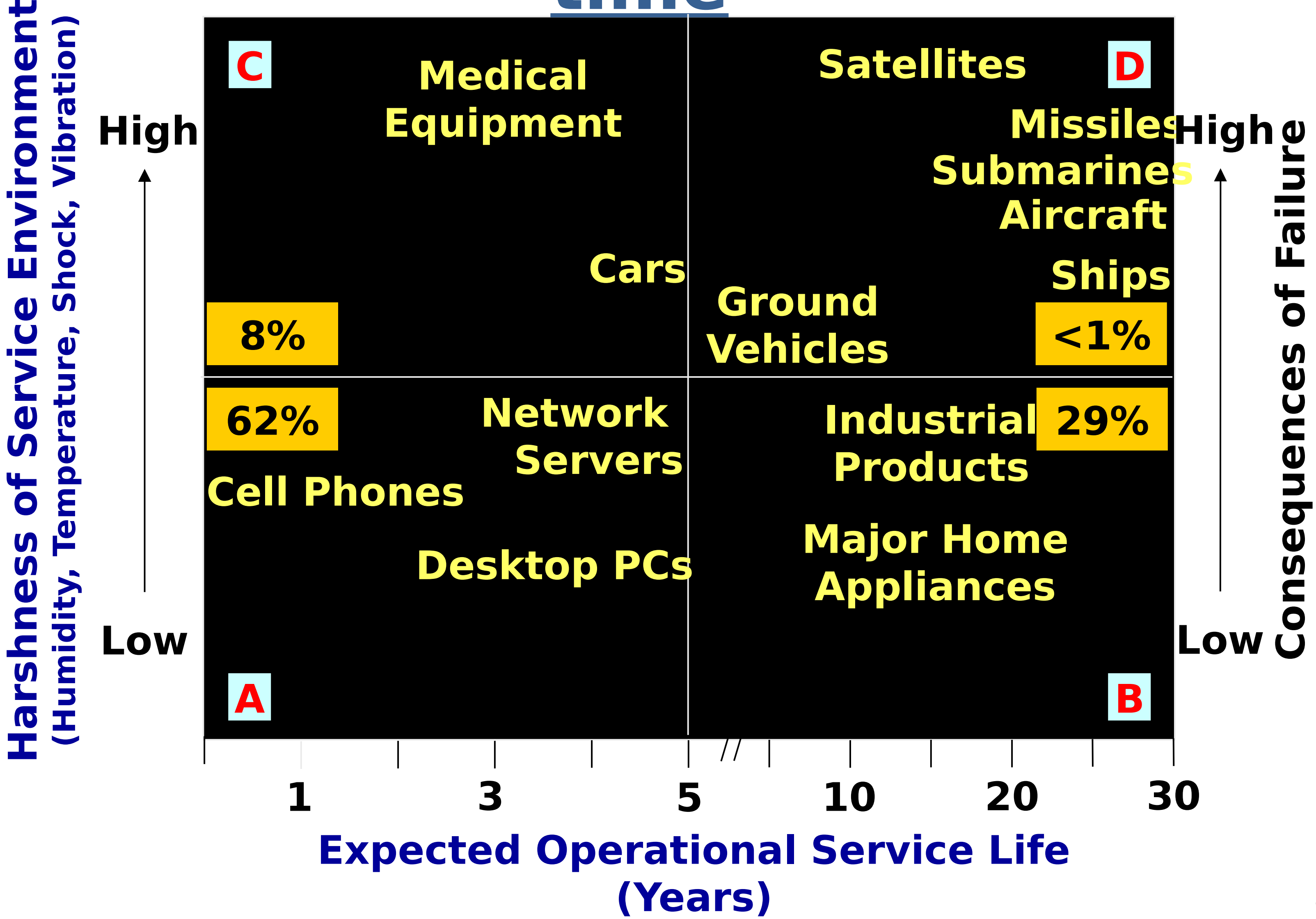
COTS suppliers are discontinuing BGAs with SnPb balls; Reballing has risk

Additional Recent Pb-free Electronics Failure

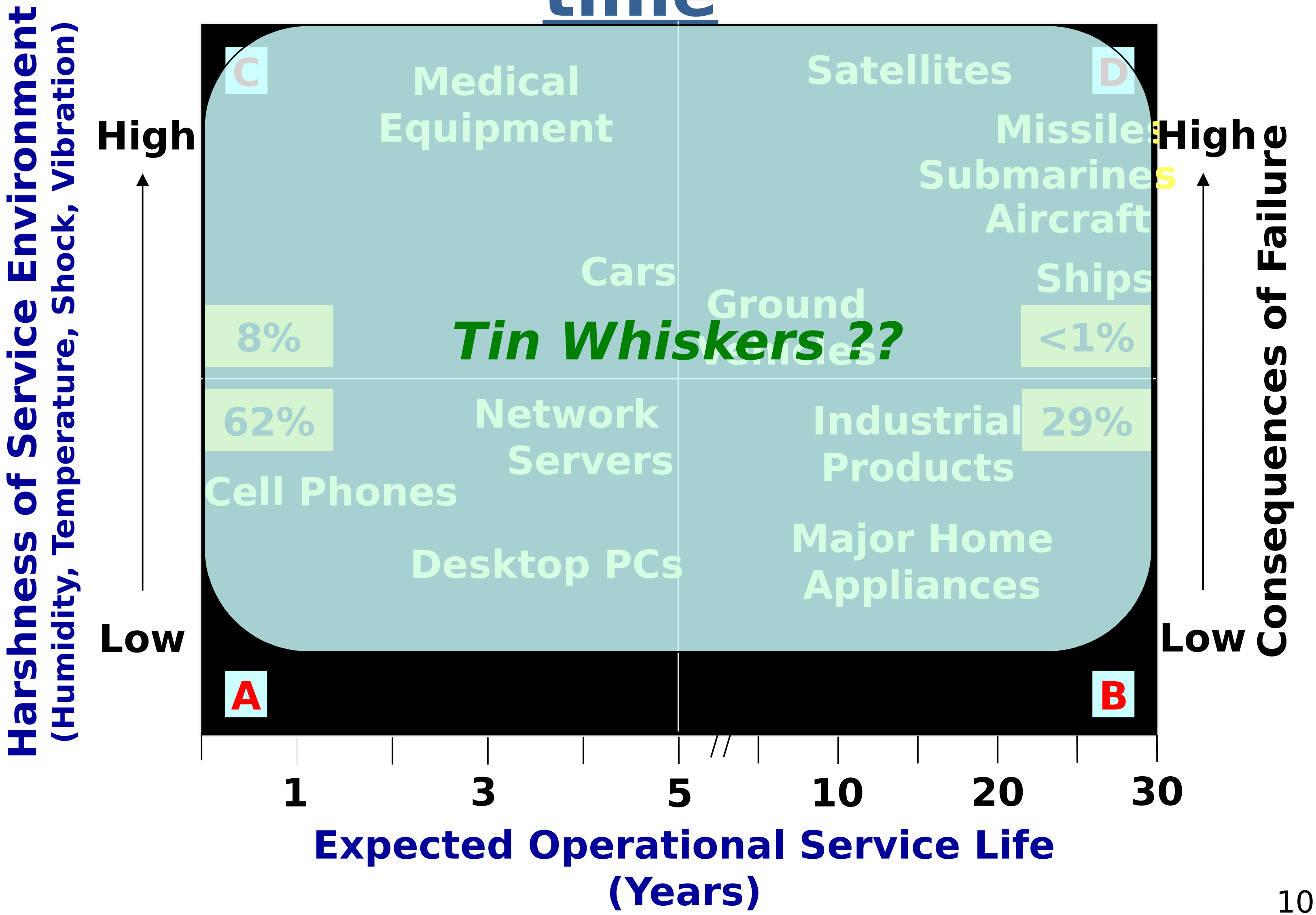
A Recent Industry Disclosure:

1. A board assembly house working on a Defense development Contract was successfully soldering lead-free BGAs of around 1000 balls onto a tin-lead PCB, but got into a problem recently.
2. The board assembler developed an oven profile which soldered the SAC 305 BGAs and the tin-lead PCB with out damaging temperature sensitive components.
3. Everything was going well until the manufacturer of the BGAs switched from SAC 305 to SAC 105 because of concerns about solder fracture during drop testing from commercial customers.
4. The BGA had the same lead-free logos on it indicating it was RoHS compliant. The markings did not reflect the alloy change of the BGA solder balls.
5. SAC 305 has a melting temp of around 221C. SAC105 has a melting temperature of 228C.
6. The profile that melted the SAC 305 BGAs did not fully melt all the SAC 105 BGA solder balls.
7. The problem was missed until an intermittently functioning BGA was found during trouble shooting. The BGA passed automated X-ray inspection. The connections were in the middle of the package and not optically inspectable.
8. **Unfortunately some of the product escaped into the field and had to be recalled.**

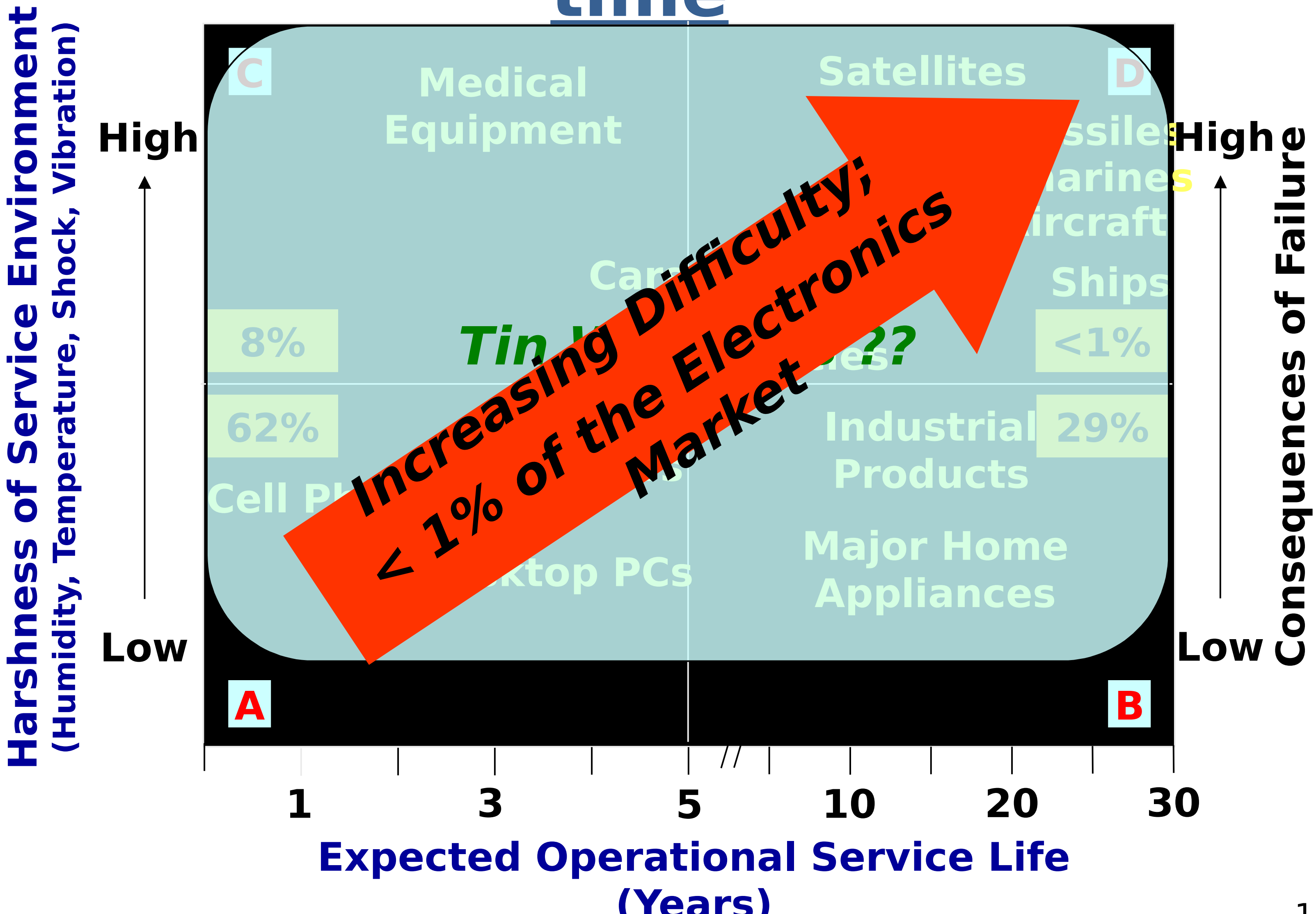
Pb-free Electronics Operating Environment vs. Operational Life-time



Pb-free Electronics Operating Environment vs. Operational Life-time

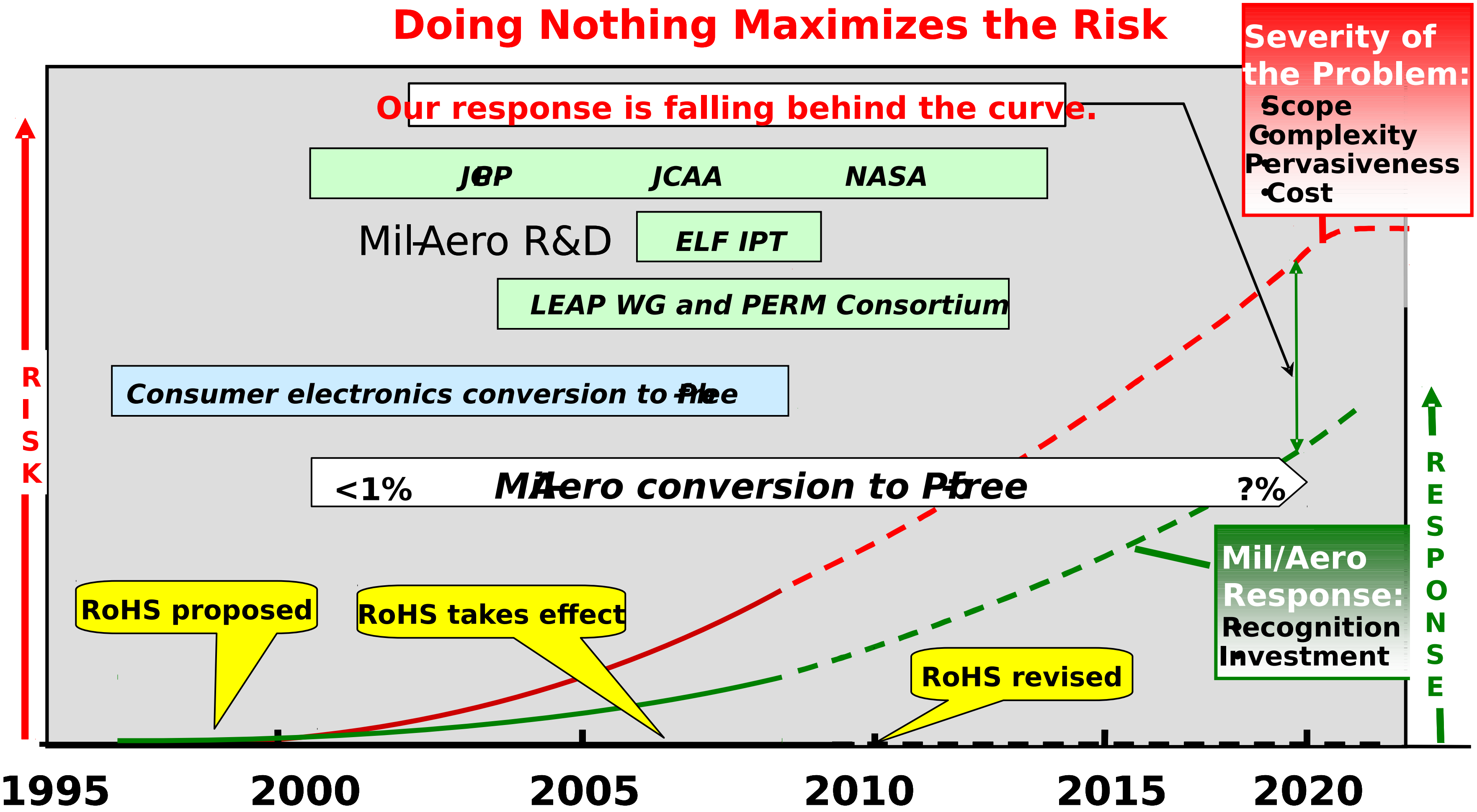


Pb-free Electronics Operating Environment vs. Operational Life-time



A&D Response to Pb-free Electronics

Doing Nothing Maximizes the Risk



JG-PP: Joint Group on Pollution Prevention

JCAA: Joint Council on Aging Aircraft

ELF IPT: Executive Lead-Free Integrated Process Team

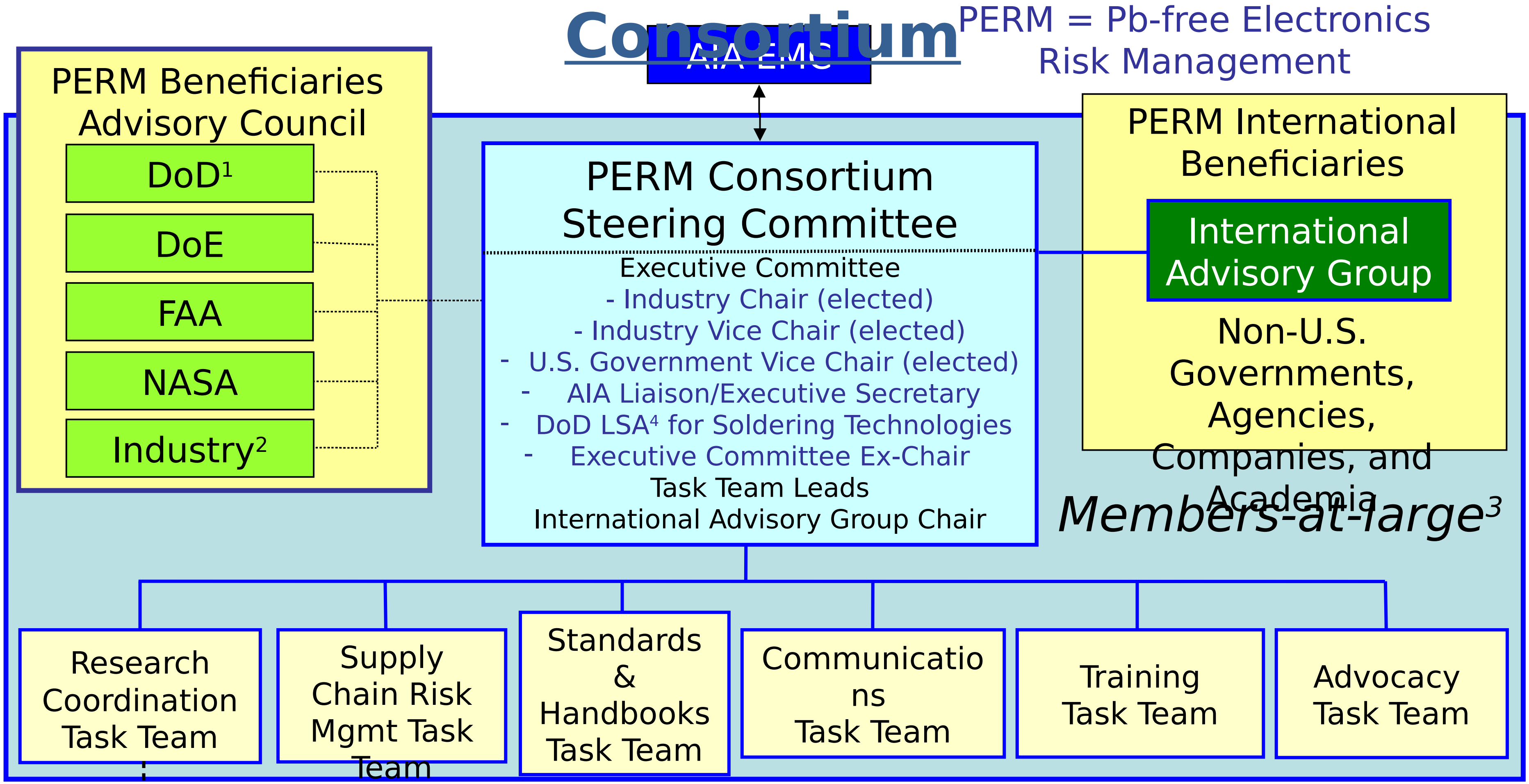
LEAP WG: Lead-free Electronics in Aerospace Project Working Group

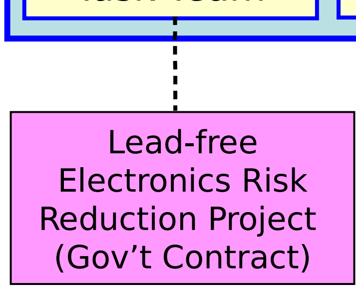
PERM Consortium: Pb-free Electronics Risk Management Consortium

GEIA Pb-free Standards and Handbooks From the LEAP WG/PERM Consortium

RELEASED	
GEIA-STD-0005-1	Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-free Solder
Lead Free Control Plan (LFCP)	Compliance Template for compliance to GEIA-STD-0005-1
GEIA-STD-0005-2	Standard for Mitigating the Effects of Tin in Aerospace and High Performance Electronic Systems
GEIA-HB-0005-1	Program Management / Systems Engineering Guidelines for Managing the Transition to Lead-free Electronics
GEIA-HB-0005-2	Technical Guidelines for Aerospace and High Performance Electronic Systems Containing Lead-free Solder
GEIA-STD-0005-3	Performance Testing for Aerospace and High Performance Electronic Interconnects Containing Pb-free Solder & Finishes Unable to Complete!!
GEIA-HB-0005-3	Rework, Repair and Maintainability for Aerospace and High Performance Electronics Containing Lead-free Solder
In Work	

Pb-free Electronics Risk Management Consortium



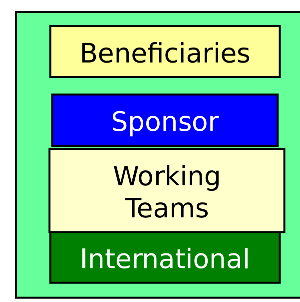


1. Membership of Senior Stakeholders determined by OSD and DoD

2. Including representatives of U.S. Industry Associations such as AIA, TechAmerica, AMC, IPC, etc.

3. Any individual participant (Government, industry and academia) in PERM meetings and consensus process; Integrated Membership from prior LEAP WG and ELF IPT

4. LSA = Lead Standardization Activity



Pb-free Electronics Risk Reduction
"Scope & Solve the Problem"

Manhattan Project **Pb-free Electronics Project**

Manhattan Project

DoD Pb-free Electronics Risk Reduction Program

ONR Funded

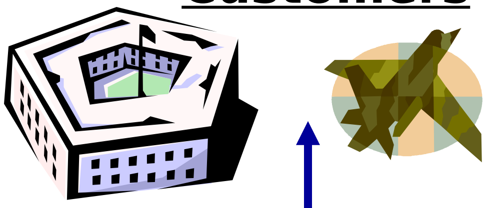
Phase 1: Best Practice Baseline – Completed

JDMTP*

Phase 2: Technology Roadmap – In Work!

* *JDMTP* = Joint Defense Manufacturing Technology Panel

Customers



DoD plus…

Phase 3 – Integrated Risk Reduction Projects

- **Tin Whiskers**
- **Electronics Assembly**
- **Solder Joints**
- **Electronic Component**
- **Printed Circuit Boards**

2009

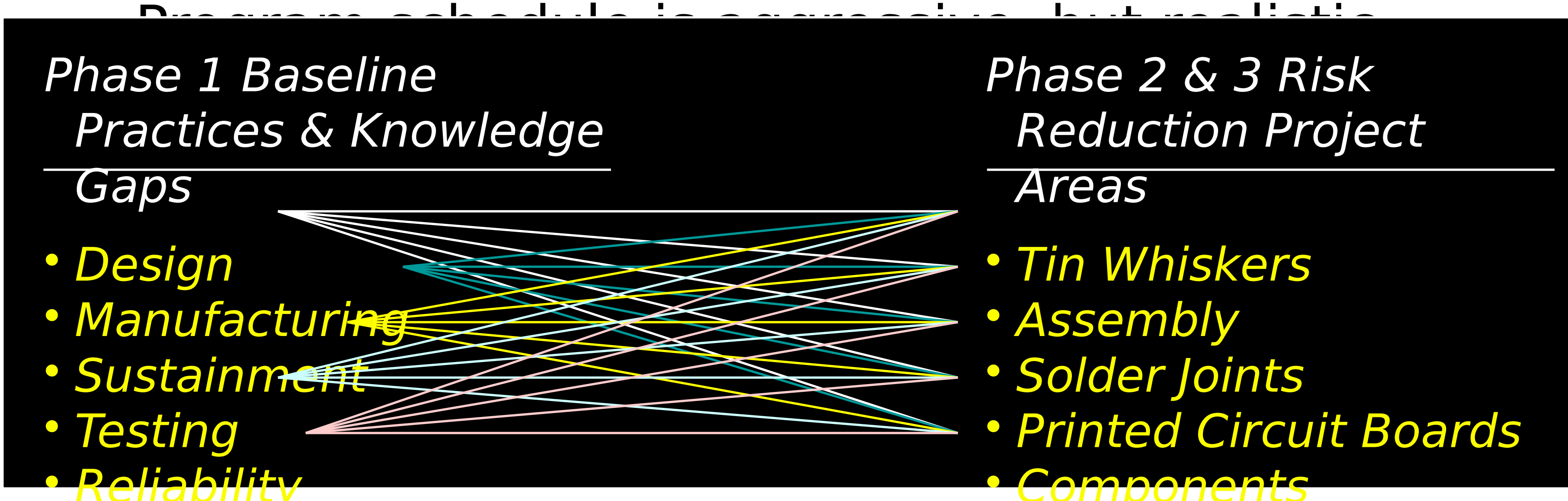
2010-2013----

Project Participants

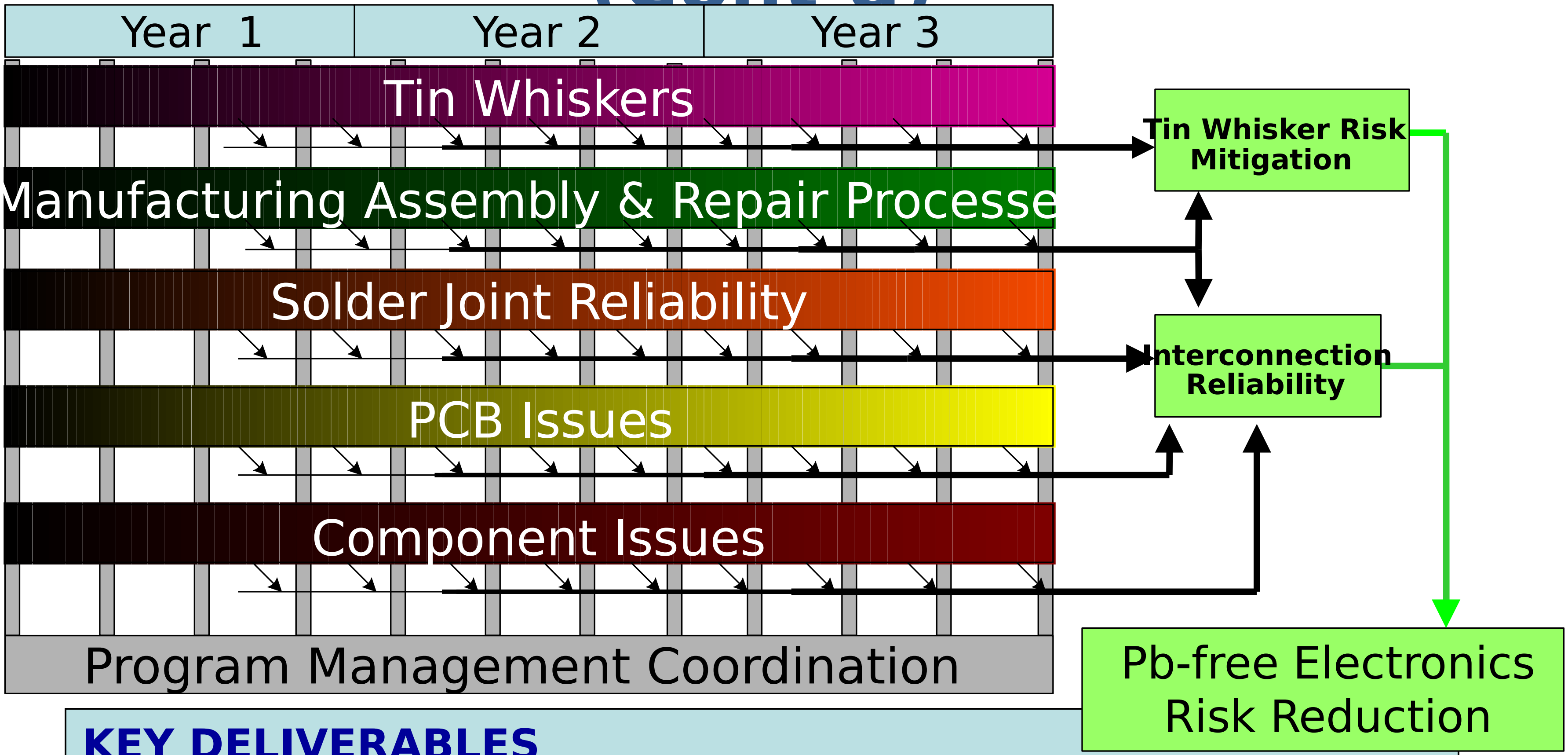
- **B2P COE Project Management:**
- **Technical Project Leadership:** (Lockheed Martin) & (Boeing) – Self-funded
- **Meeting Moderator:** Howe School of Technology Management, Stevens Institute of Technology
- **SMEs:**
  - (Universal Instruments/Unovis)
  - (Boeing)
  - (Purdue University)
  - (DfR Solutions)
  - (Rockwell Collins)
  - (Honeywell)
  - (AMRDEC)
  - (BAE Systems)
  - (Univ. of Maryland CALCE)
  - (Raytheon)
  - (Raytheon)
  - (Celestica)
  - (ACI)
  - (Sandia National Labs)
  - (NIST)
  - (Boeing)
  - (Lockheed Martin)

Phase 1 & 2 Observations

- Serious technical gaps exist for Pb-free electronics that have to be overcome for use in DoD harsh environment
- Quantification of degraded reliability and lifetimes is a significant gap
- The three-year Pb-Free Electronics Risk Reduction Program schedule is aggressive, but realistic



Recommended Roadmap for Pb-free Electronics Risk Reduction (Cont'd)



KEY DELIVERABLES

- ***Detailed Design Guidelines for Use of Pb-free COTS Electronics***
- ***Validated Life-Prediction Models based on Physics of Failure***
- ***Methodologies for Assessing New Materials***

ROM Cost Estimate

36-month Risk Reduction Program will enable continued use of COTS electronics in DoD products

WBS	Risk Reduction Project Area	ROM Cost in 2010 $ (M)			
		Year 1	Year 2	Year 3	TOTAL
A	Tin Whiskers	$ 6.3	$ 6.8	$ 6.5	$ 19.7
B	Assembly	$ 3.2	$ 4.0	$ 3.0	$ 10.2
C	Solder Joints	$ 13.9	$ 19.4	$ 13.3	$ 46.6
D	Components	$ 1.2	$ 2.6	$ 2.1	$ 5.9
E	Printed Circuit Boards (PCBs)	$ 3.9	$ 5.2	$ 3.5	$ 12.6
	TOTAL	$ 28.5	$ 38.0	$ 28.5	$ 95.0
	TOTAL with 10% Contract Administration Cost	$ 31.4	$ 41.8	$ 31.3	$ 104.5

Program Execution Budget Required in 2010 Dollars: $105M

Fundamental objective is to resolve knowledge gaps for use of Pb-free electronics as quickly as possible!

Program Execution Agency: ONR

ONR ManTech Has Maintained a Leadership Role in Lead Free

- **Navy ManTech Projects**
  - Process Development with Navy Electronics Hardware
  - Initial Reliability Assessments
  - Industrial Collaboration through ONR ManTech's IAB
- **Executive Lead-Free IPT (ELF IPT)**
  - IAB Collaborated on Issues Effecting the Management of Lead-Free
    - Development of Training
    - Recommendations for DoD Policies
    - Business Case Analysis
    - Developing Roadmaps – Current Work Collected

(Precursor to Manhattan Project)

- **ONR and JDMTP Sponsored Manhattan Project**
  - Development of Baseline Practices (Published Book)
  - Development of Roadmap, Gaps, and Needed Research
    - **A Path to Resolution to Ensure DoD Hardware Reliability**

DoD R&D Return on Investment (ROI) Analysis

Forecasted Future Annual DoD O&S Repair Cost from Pb-free Electronics Failures

(Does not include mission impact cost or loss of platforms)

- **Current Defense Electronics Infrastructure: ~$50B fielded inventory**
  - **Defense electronics procurement of $10B/year with electronics average life >5 years = $50B**
  - **>5M LRUs fielded at an average value of <$10K = $50B**

- **Assumptions**
  - **Additional 1% failure rate per year without R&D mitigations**
    - **"One OEM has recently indicated privately that their returns are already up more than 3% compared to products produced with traditional solders"** - Global SMT & Packaging, April 2006
  - **$1K repair cost per LRU failure**
  - **All failed Pb-free LRUs are repairable**

- **Increased Repair Cost at Full Pb-free Electronics Introduction: $50M/year**

Pb-free Electronics Risks Technical Discussion…

Combined Current Annual Spending for 8 Large Industry OEMs

- **Lead-free Electronics Risk Mitigation Investments Initiated as Early as 1992, Most Starting in 2001**
  - Enterprise Project Level: ~ $5.0M/year
    (these are overhead dollars)
  - Advanced Technology Project Level: ~ $3.4M/year
    (these are specific funded project dollars)
  - Industry Consortia Pb-free Directed Funding: ~ $850K/year
  - University Specific Directed Funding: ~ $1.5M/year
  - Industry Association Activities: ~ $850K/year
    (IPC, SMTA, LEAP, PERM ,HDPug, SMART etc.)

Total: *~$11.6M/year*

- **Industry Participation in Special Lead-free Electronics Programs**
  - AT&T Project: **1992-2000 @ $1.5M**
  - NCMS Pb-free Project: **1993-1997 @ $11M, 1996-2001 @ $10.2M**
  - JCAA-JGPP Pb-free Project: **2003-2007 @ $2.0M**
  - NASA DoD Project: **2007-in progress @ $1.8M**

Financial Implications of Retaining SnPb

- **Discrete Semiconductors**
  - These parts typically cost from $4 to $0.2 but usage is high
  - Some component suppliers still providing SnPb finished parts, but….
    - One OEM assessment finds:
      - o **$300K/yr** to purchase SnPb instead of the Tin equivalents
      - o **25 week** Lead-times encountered often

- **Incoming inspection for SnPb**
  - Pb-free findings have high impact to production in "just in time" production
    - NASA Finding: **~5% of parts specified to be SnPb are coming in with the Pb-free finishes**

- **OnSemi Product Change Notice (PCN)**
  - Product Change Notice PCN 16389
    - 4Q09 (4th QUARTER 2009) Product Discontinuance Notice
    - LAST BUY DATE: 21-Jul-2010
  - 456 SnPb parts being replaced by Pure tin parts
    - Parts disposition program by program
      - o Use as is – but what is whisker risk?
      - o Reprocess to get SnPb altered part
      - o Life time buy

Base part	Part	Status	PLATING							
			Sn [%]	Pb [%]	Ag [%]	Cu [%]	Pd [%]	Au [%]	Ni [%]	Weight [mg]
			7440-31-5	7439-92-1	7440-22-4	7440-50-8	7440-05-3	7440-57-5	7440-02-0	
1.5SMC47A	1.5SMC47AT3	Lifetime	80.00	20.00						2.51
1.5SMC47A	1.5SMC47AT3G	Active	100.00							2.51
	SZ1.5SMC47AT3	Obsolete	80.00	20.00						2.51
	SZ1.5SMC47AT3G	Active	100.00							2.51

- Sample: BAS16LT3 Diode, 75V, 200MA
  - o **1908 configurations** (production or fielded) use this part
  - o **105 programs** (or variants) impacted

$$ Impact: All DoD OEMs are evaluating their use of these 456 parts

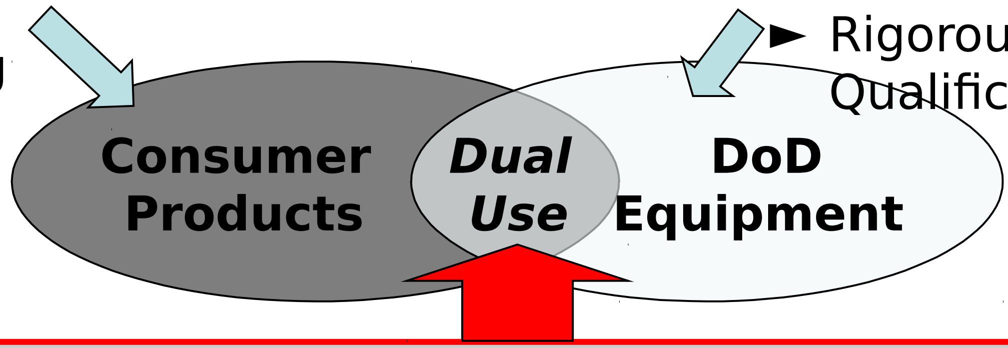
Maintaining SnPb Requires Significant Effort

DoD COTS Electronics Dependence

Commercial versus DoD Electronics Usage

- ► 1-2 Year Life, No repair
- ► Non-Safety Systems
- ► "Fractions of a Cent" Cost Drivers
- ► RoHS Compliant
- ► Rapidly Changing

- ► Complex Systems
- ► 10-20+ Year Service
- ► High Performance
- ► Critical Safety Items
- ► Rigorous Qualification



Consumer Electronics Supply Base Will Not Accommodate or Solve DoD Harsh Operating Environment Reliability Issues

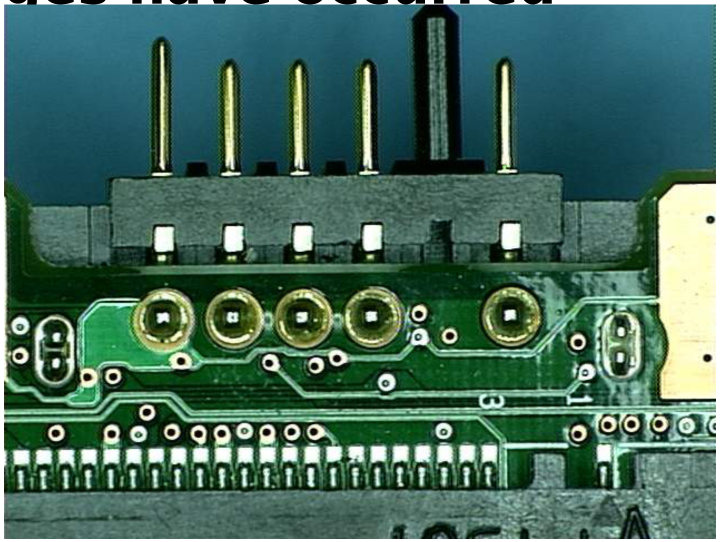
- Many, but not all Pb-free electronics issues for consumer products will be resolved by commercial electronics manufacturers (mostly in China & Asia)

- COTS electronics issues to be solved for DoD applications:
  - Tin whiskers
  - Reliable operation in harsh environments
  - Repair and sustainment

What Has Changed?

Early Lead-Free Electronics Adopters ✉ Consumer Segment

Numerous technical PCBA changes have occurred



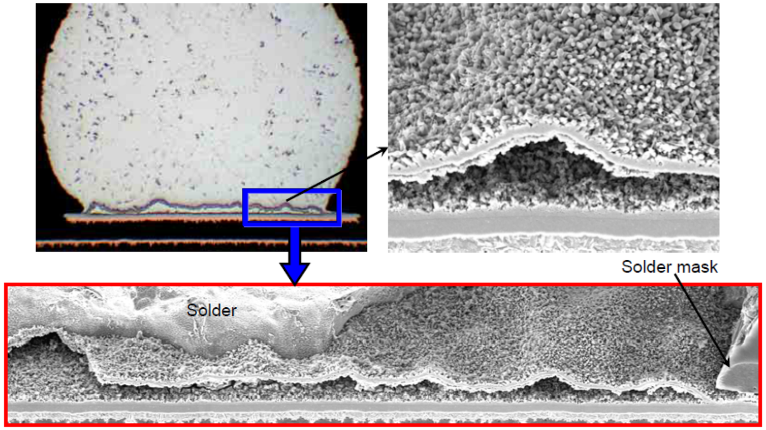
- **Resultant Material Changes**
  - Laminate Materials
  - Surface Finishes
  - Component Constructions
  - Alloy Selection
  - Addition of Underfills
  - Fluxes
  - Repair and Cleaning Chemistries
- **Resultant Process Changes**
  - SMT
  - Wave
  - Hot Gas Rework
  - Solder Fountain Rework
  - Hand Repair
  - Test & Inspection
  - Mechanical Hardware, Assembly, and

Ref: "High Reliability Lead-Free Server / Storage Hardware Assembly and Test: Successes & Remaining Challenges," Matt Kelly, IBM Corp. , April 2009 briefing to the LFMP

Much more than solder is changing – Each material and process change must be proven before critical system use

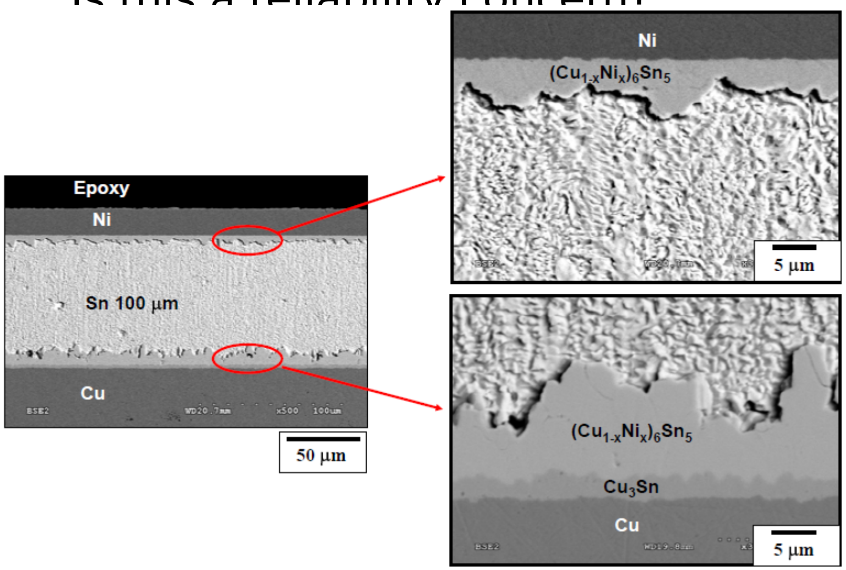
Pb-free Solder Questions
"Things Never Seen with Tin-Lead"

- **Intermetallic Spalling**
  - Some reflow situations result in intermetallic lifting off the pad while everything is liquid.
  - Example presented is extreme – is this an outgrowth from more subtle behavior actually observed in practice?
  - Is this a reliability concern?



SAC305 on Au/Ni Reflow 300s results in massive intermetallic spalling

- **Cross Diffusion of Ni and Cu through Sn.**
  - Ni from top pad diffuses through Sn to bottom pad and forms $(Cu_{1-x}Ni_x)_6Sn_5$ intermetallic (IMC)
  - Cu diffuses through Sn to opposite pad and interacts with Ni to form intermetallic
  - Is this thick IMC a reliability concern?
  - Is this worse with high current densities?

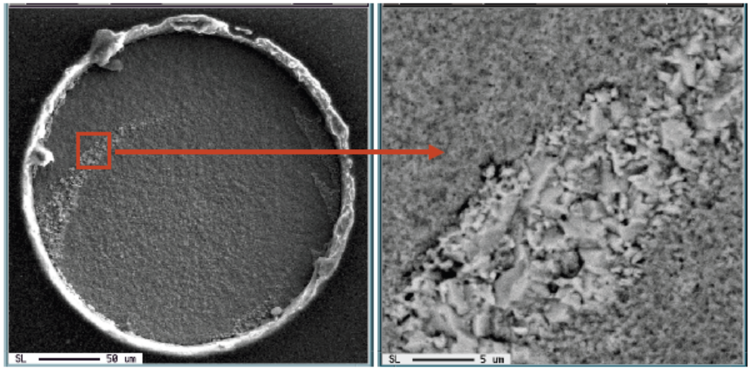


Aging 100 hrs at 200 °C

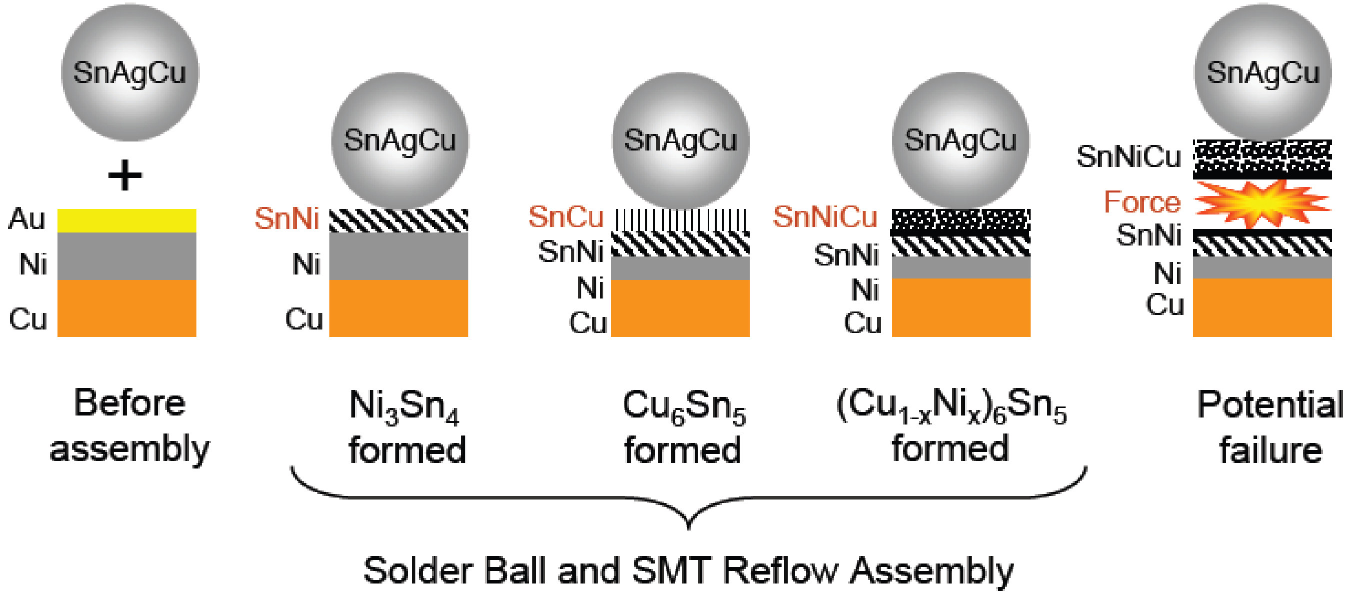
(Ref: Kao, "Cross-Interaction Between Cu and Ni in Lead-Free Solder Joints", TMS Workshop 2006)

Pb-free Solder Issues "Things Never Seen with Tin-Lead"

- **Intermetallic Fracture**
  - With Cu supplied by the solder, attaching to Nickel pads can be problematic
  - $(Cu_{1-x}Ni_x)_6Sn_5$ intermetallic IMC forms over a layer of Ni_3Sn_4 at the nickel pad
  - The Ni atoms are substituted on the Cu lattice
  - Weak boundary between intermetallics
  - Mechan



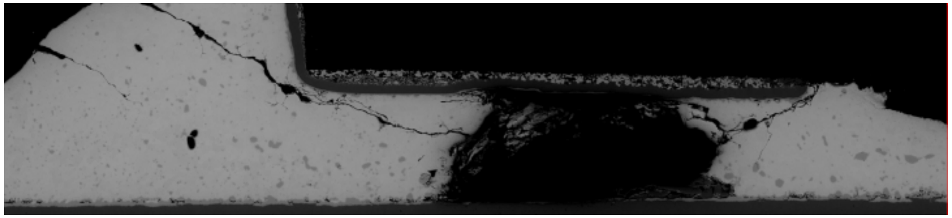
Brittle fracture between intermetallic



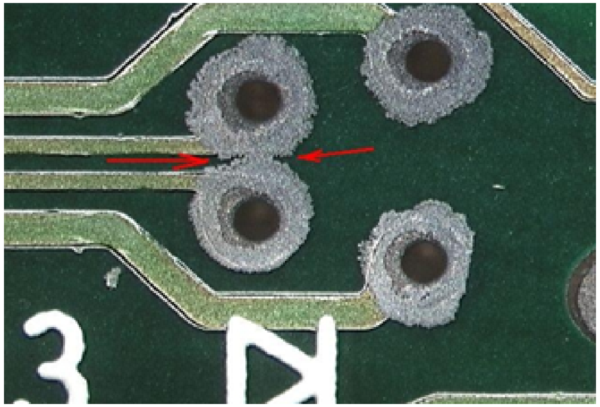
(Ref: Gregorich et.al, "SnNi and SnNiCu Intermetallic Compounds Found When Using SnAgCu Solders", IPC/Soldertec Global 2nd International Conference on Lead Free Electronics June 23, 2004)

Pb-free Solder Questions “Things Never Seen with Tin-Lead”

- **Solder voids suspected to significantly reduced thermal cycling life.**
  - Failure occurred after 85 cycles (approximately 5 days of accelerated thermal cycling)
  - Will SnPb environmental stress screening be effective for Pb-free?
  - What about other Pb-free alloys?
  - What about vibration and shock?



Sn0.7Cu0.5Ni0.05Ge chip resistor cross-section after thermal cycling. (Ref. CALCE)



Schueller, ”Creep Corrosion of Lead-Free PCBs,” SMTA Conf. Proc. 2007

- **Silver + Sulfur = Corrosion**
  - Immersion silver is a leading Pb-free circuit board finish
  - Concerns in sulfur and high humidity environments include Cu corrosion, electrochemical migration and silver whiskers
  - Will existing MIL-STD-810 salt fog tests catch this?
  - MIL-STD-810 does not include sulfur environments

Pb-free Solder Questions
"Things Never Seen with Tin-Lead"

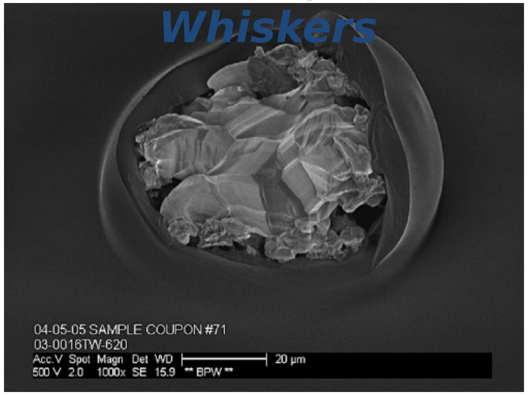
- **Conformal coats fractured by tin whiskers and odd shaped eruptions**
  - Many conformal coats ruptured by whiskers
  - System considerations
    - Whisker penetrating coating can continue to grow and shorting risk increases with time
    - Fractured coating results in electrical leakage paths in humidity

~2-Year Test

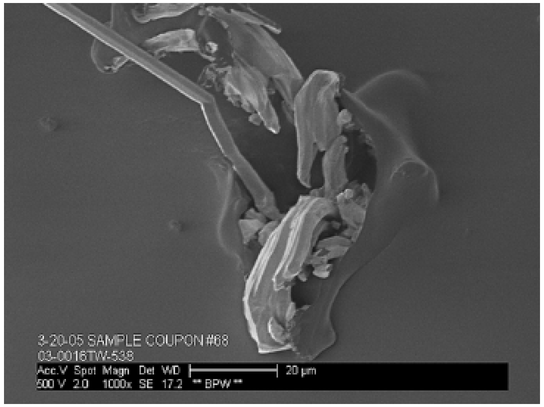
"Rapid Whisker Growing Substrate"

401 Days at Ambient + 347 Days in 25°C/97%RH, Bright Tin over Brassass

Conformal Coatings Ruptured by Whiskers



2.9 mil thick silicone

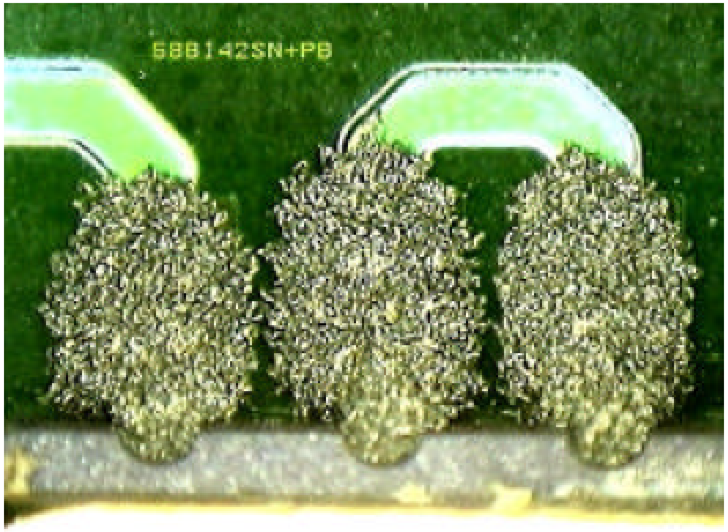


1.1 mil thick acrylic

(Ref. Woodrow, "Evaluation of Conformal Coatings as a Tin Whisker Mitigation Strategy, Part II," SMTA International Conference Proceedings, September 24-28, 2006)

Pb-free Solder Questions
"Things Never Seen with Tin-Lead"

- **Mixing SnPb alloys with Bismuth bearing Pb-free solder joints can spell trouble**
  - Trace amounts of lead (Pb) can decrease the reliability of bismuth–containing solders
  - The effects of trace amounts of lead on 58Bi42Sn are catastrophic
    - Solder joints essentially turned to powder during thermal
  - **Important because SAC Bismuth alloys have demonstrated the best reliability**
  - **DoD sustainment infrastructure will have SnPb for many more year, probably forever**

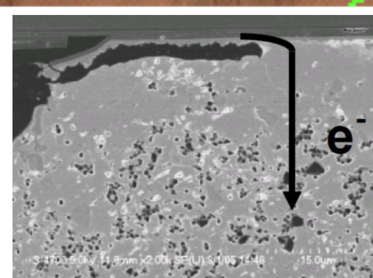


58Bi42Sn Joints contaminated with Pb
(after 835 Thermal Cycles -55 to +125 °C)
Suspect issue with SnPbBi ternary eutectic (T_{melt} = 96 °C)

(Ref. Woodrow, "The Effects of Trace Amounts of Lead on the Reliability of Six Lead-Free Solders," IPC Proceedings of the 3rd International Conference on Lead-Free Components and Assemblies, San Jose, CA April 23-24 (2003)

Pb-free Solder Questions “Things that Have Challenged Us Before with Tin-Lead”

- **Electromigration, Small Joints, High Current Densities**
  - Electron wind and current crowding yields
    - Copper pad dissolution at current densities on the order of $1x10^{-4}$ A/cm^2 which is important for flip chip interconnects.
    - Single grained solder joints often occur with small joints.
      - Cu diffusion rates depend upon grain
    -

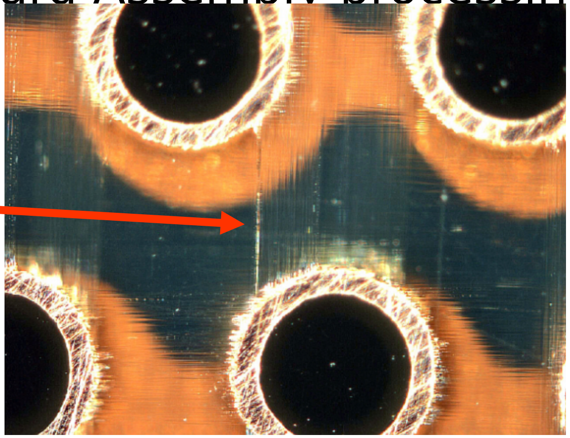


K.N.Tu “Thermo-Electromigration in WL-CSP Pb-Free Solder Joints”, HDPUG Consortium Project with National Instruments 2007-2009

Pb-free Electronics Technical Impact

- **No universally acceptable technical solutions in sight to replace SnPb in Aerospace & Defense (A&D) applications**
  - Conformal coatings only mitigate tin whiskers
  - Pb-free solder joint reliability decreased for shock; some have corrosion issues and incompatibilities with tin-lead
  - SAC305 solder dissolves copper, impacting rework and repair
  - Conductive Anodic Filament (CAF) problem is re-emerging due to higher Circuit Card Assembly processing temperatures using Pb-free solders

Conductive Anodic Filament (CAF) in Circuit Card Assembly (CCA)

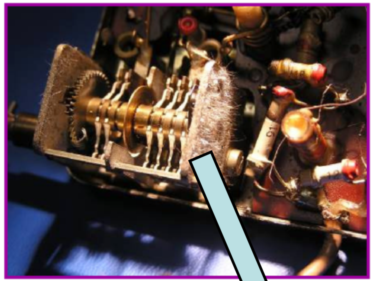


Ref: "Lead Free PCB Projects Update," Wayne Jones, Advanced Research of Electronic Assemblies Consortium, February 2008

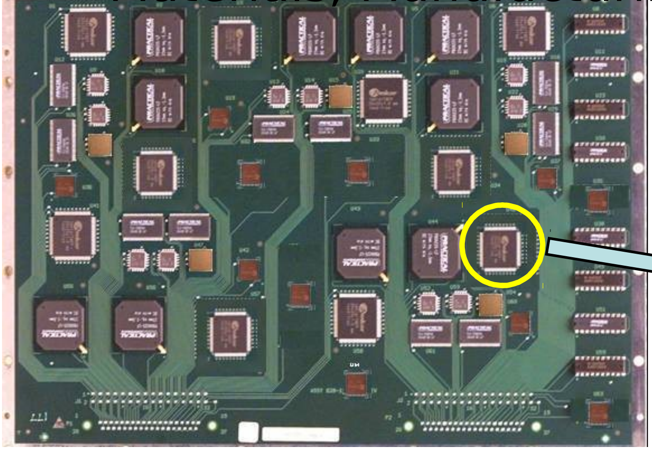
Current technical approaches are all still "mitigations" and not "elimination" of the Pb-free electronics issues

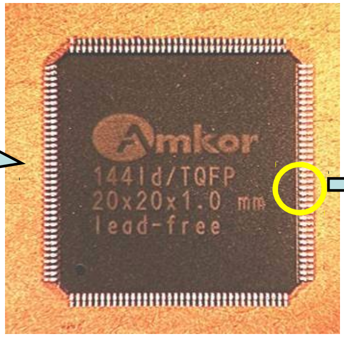
Tin Whiskers

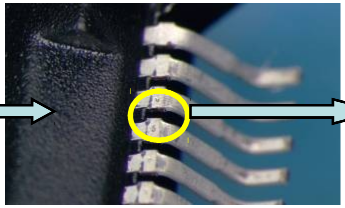
- Whiskers are filament-like structures that:
  - Are ten-times smaller in diameter than a human hair
  - Grow long enough to bridge between conductors
  - Are electrically conductive
- Tin whiskers form spontaneously from tin finishes and Pb-free tin alloys
  - Since the 1950s, Pb has inhibited tin-whisker growth
- Various factors (or combination of factors) cause growth:
  - Materials, Manufacturing, Environment

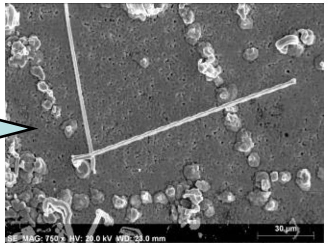


Tin Whiskers on 1960's era Variable Air Capacitor



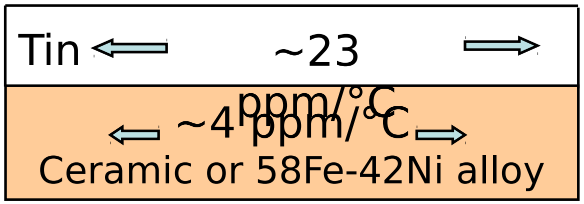




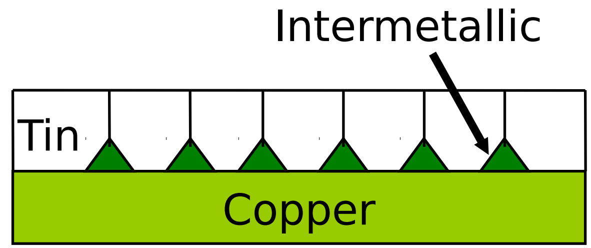


Theories on Basic Whisker Growth

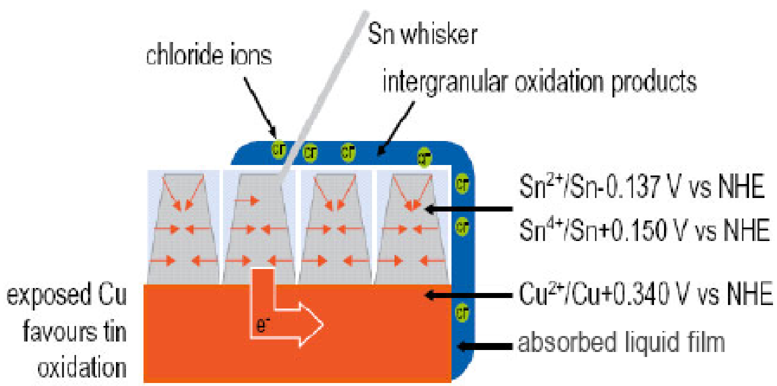
Compressive stress in tin is believed to cause to whisker growth



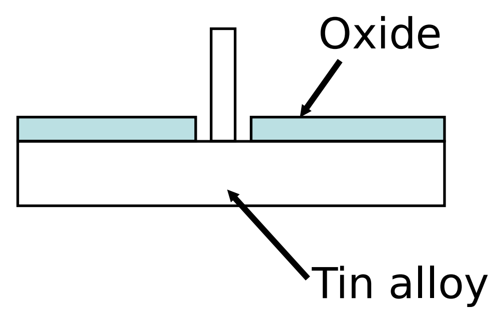
Thermal cycling — coefficient of thermal-expansion-driven stress



Intermetallic growth increasing tin stress



Corrosion and electro-migration increasing tin stress



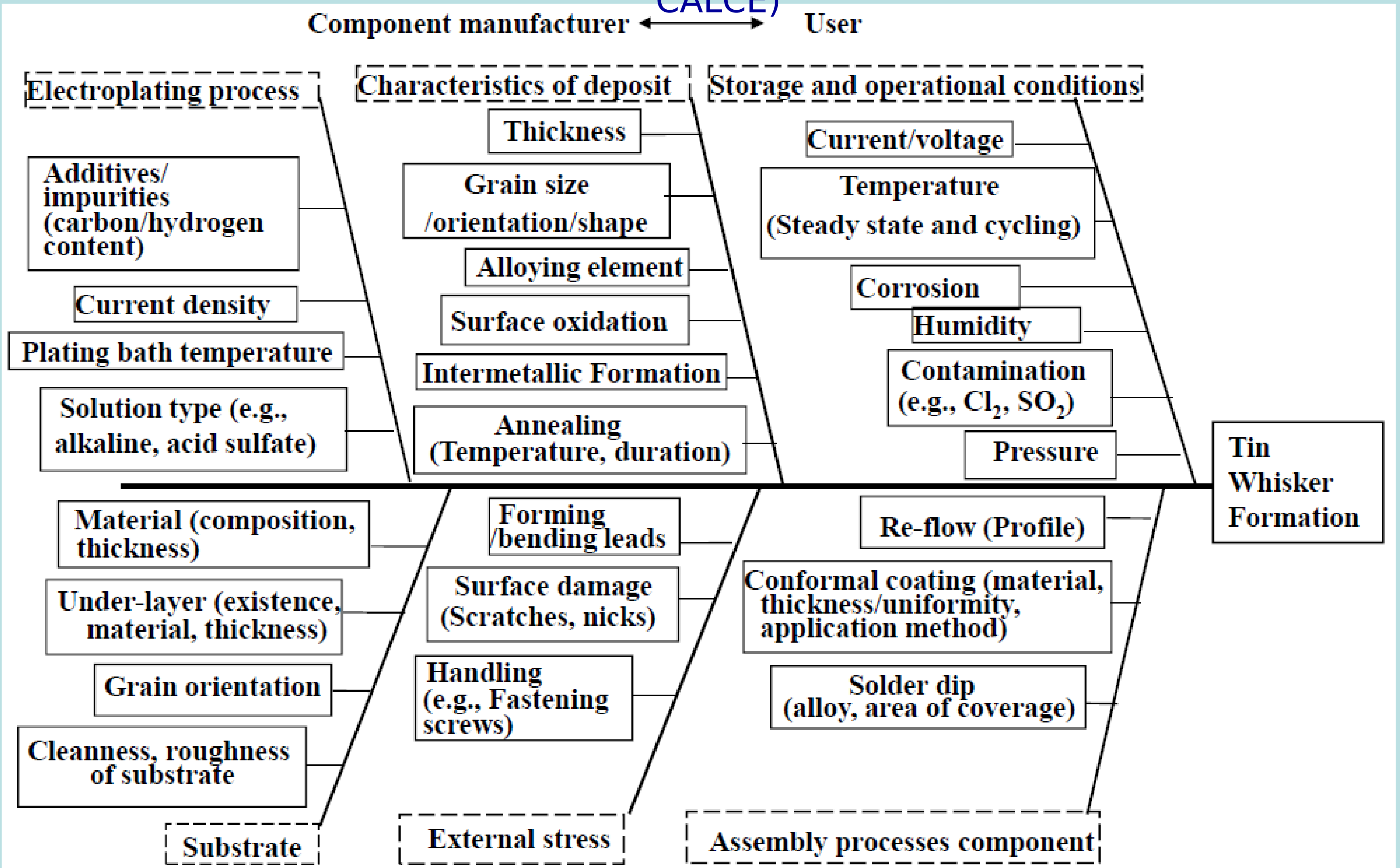
Oxide facilitates increasing stress

- **Military electronics are exposed to all of these conditions**
- **We need to understand the entire system to**

Tin Whisker Risk

Whisker growth has many factors

(Ref: “2007 CALCE Tin Whisker Symposium,” Michael Osterman, CALCE)

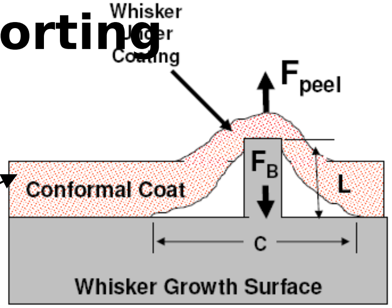


Tin Whisker Risk (Cont'd)

Tin whisker conformal coat mitigation & deficiencies

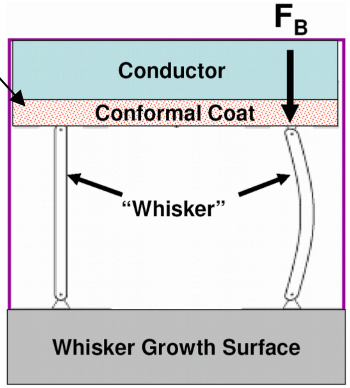
Conformal Coat Mitigation

Coating insulation inhibits shorting



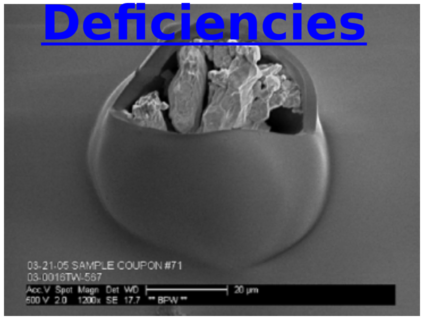
Temperature and humidity coating properties

Coatings can capture whiskers…



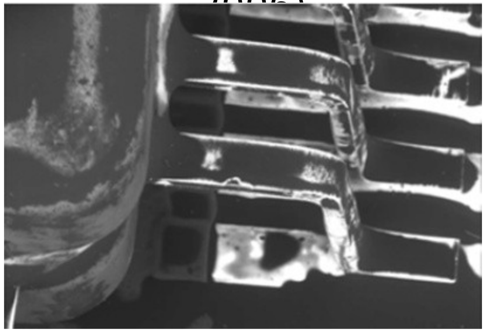
and prevent contact

Conformal Coat Mitigation Deficiencies



Tin growth breaching silicone conformal coating

(Ref: Tom Woodrow, Boeing, SMTA 2006)



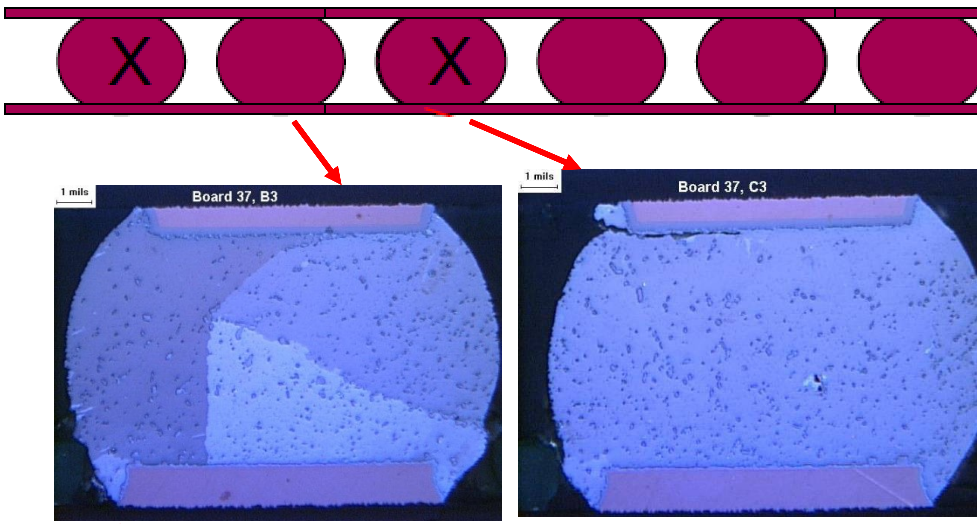
Coating coverage (black) lacking on leads (white)

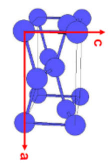
(Ref: CALCE/BAE, 2009)

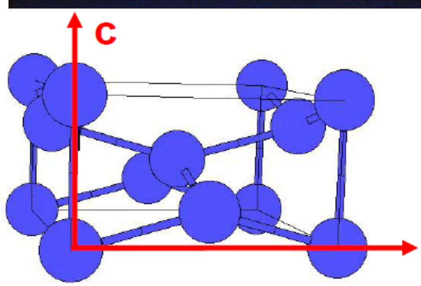
- **Thousands of parts with pure tin finish are being introduced into DoD Systems**
- **Science lacking to quantify decrease in system reliability**

SAC Alloy Is Mostly Sn But Sn Is Very Anisotropic

Particularly rapid cracking if c-axis is parallel to pad surface







a=5.832A, **c**=3.182A

c direction expands and shrinks more with a temperature change

c direction is more stiff while

a direction is more compliant

	T_{melt} (°C)	T_{use}/T_{melt}
Tin-37Lead	**183**	**87%**
SAC305	**218**	**81%**
Tin	**232**	**79%**
Aluminum	**660**	**43%**
Copper	**1085**	**29%**
Iron	**1538**	**22%**

Direction < >	Thermal Expansion Coefficient (10^{-6}/°C)	Young's Modulus (Gpa)
	23[1]	41[1]
c <001>	30.5[2]	67.6[3]
a <100>	15.4[2]	23.6[3]

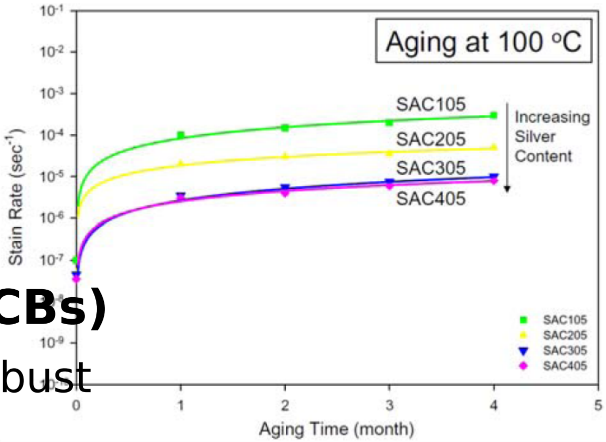
Solders are at "used ~80% of their melting point at 125°C – Diffusion of precipitates and creep significant

(Ref: E. Cotts, Binghamton University)

Pb-free Solder Is More & Less Reliable!

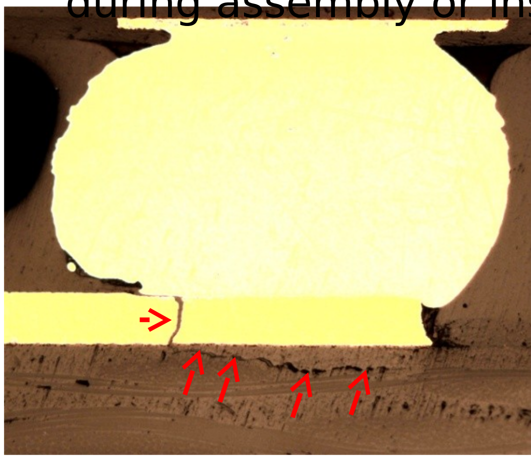
It is not easy to specify operating conditions under which Pb-free solder is consistently at least as good as SnPb

- **Thermal cycling results in solder failures**
- **Pb-free alloy fatigue life unclear in service**
  - SnPb is favored with longer dwells at high temperature
  - **Properties of lead-free continue to degrade, some to an extreme extent, for decades in long-term service**



(Ref: Dr. P. Lall, CAVE3 Consortium)

- **Pb-free impacts printed circuit boards (PCBs)**
  - Bond between SnAgCu alloys and Ni pads are less robust
  - Pb-free compatible PCBs are more brittle
  - Pb-free solders stress pads more
  - **Pad cratering premature failure risk** (Undetected “Invisible” pad damage during assembly or installation may lead to failure in service)

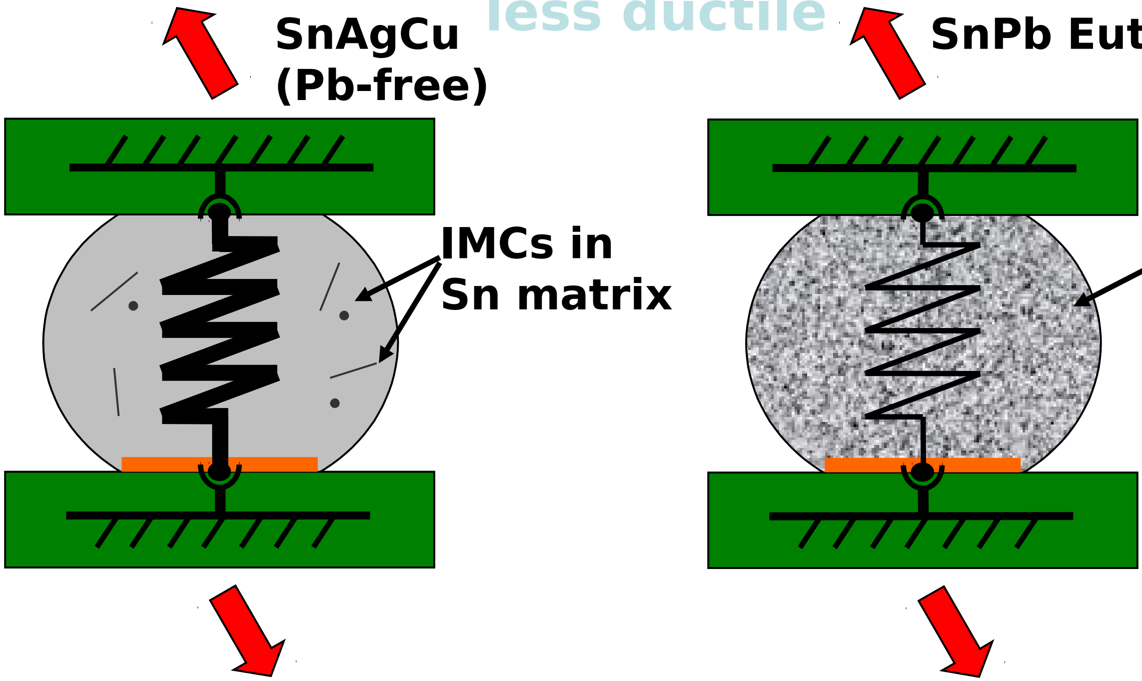


- **Vibration, drop shock, etc., more commonly result in other failures**
  - Pad cratering under the solder pad
  - Intermetallic bond between the solder and the pad
  - **In either case, Pb-free alloy is consistently less reliable**

(Ref: Dr. Peter Borgesen, Universal Instruments AREA Consortium)

Pb-free SnAgCu (SAC) Solder Mechanical Response

Pb-free SnAgCu solder applies more stress to pads and is less ductile



BGA Solder Joint Mechanical Integrity

(Ref: Denny Fritz – SAIC "Tin whisker" telecon presentation, July 25, 2007)

Mechanical response failure mode for SAC solder is pad cratering

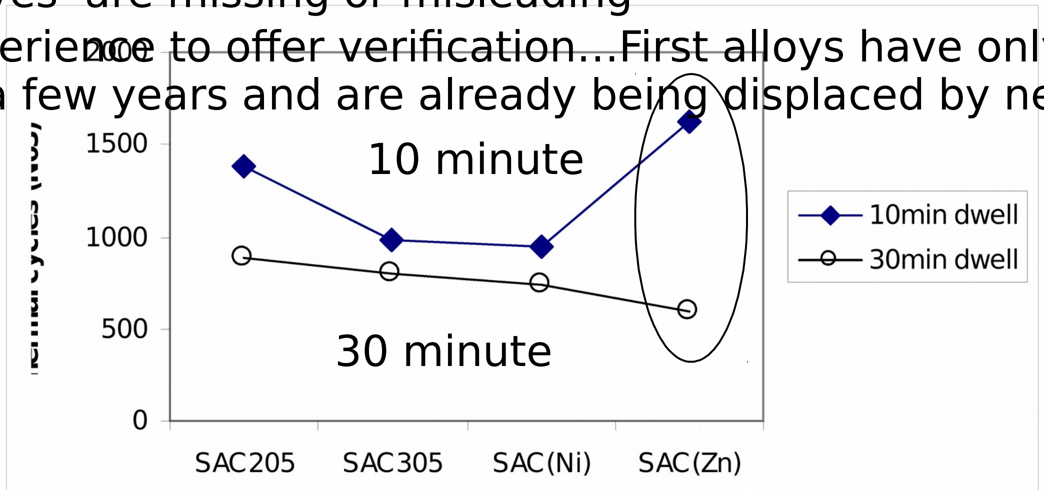
Contributing to pad cratering are the new Pb-free compatible PWB materials because they are more brittle

Pb-free Solder – Keeping Up with the Technical Publications

- **Public Compendium by DBI Corp.**
  - Over 16,000 lead-free related publications identified (http://dbicorporation.com)
  - Articles provide clues → Many are incomplete
    - Provide dimensionless ratios to show reliability trends
    - Leave out key data to protect proprietary information
    - For commercial temperature regimes
- **NASA Goddard Tin Whisker Site**
  - http://nepp.nasa.gov/WHISKER/
  - Basic information and FAQs
  - 270 references and anecdotes
  - Photo and video libraries
- **GEIA-HB-0005-2 – "Technical Guidelines for Aerospace and High Performance Electronic Systems Containing Lead-free Solder and Finishes"**
  - Industry handbook issued November 2007
  - Compiled by Aerospace and Defense (A&D) experts
  - 163 technical papers cited
    - Identifies areas of
      - A&D concurrence
      - Data conflicts
      - A&D testing
      - Data deficiencies

Predicting Reliability

- **SnPb materials properties are largely independent of joint size**
  - Vast accelerated test data bases could be scaled onto 'Master curves' based on modeling of mechanics
  - Decades of field experiences offered sanity checks for extrapolations of test data
- **Lead free solder properties vary with joint size, processing, history, and alloy dopants**
  - 'Master curves' are missing or misleading
  - No field experience to offer verification…First alloys have only been in service for a few years and are already being displaced by newer ones



- **Models can't even interpret comparisons**
  - Current thermal cycle models cannot account for one SnAgCu alloy being **best** in test with 10 minute dwell but **worst** with 30 minute dwell
  - **Depending on service conditions predictions of current models may easily be in error by 1-2 magnitudes (life of 1**

Predicting Reliability (Cont'd)

- **Errors may be *even greater* because of aging & cycling effects**
- **Also not accounted for:**
  - Ongoing coarsening of secondary precipitates gives strong solder properties changes
  - Strain enhanced coarsening and dislocation structure formation make properties vary with joint location
- **Cannot rely on Mil-HDBK-217, Military Handbook for "Reliability Prediction of Electronic Equipment" to assess system reliability**
- **As of January 2010, technical consensus lacking to complete**

"It is the judgment of the team that the use of Pb-free electronics in products whose life-cycle includes operation in and through harsh environments, poses technical risks that can lead to degraded reliability and reduced lifetimes. Quantification of these technical conclusions within valid statistical confidence bounds remains a gap. Further reliability data is needed in order to unite the existing prediction methodologies, and provide acceptable modeling accuracy."

– ***Manhattan Project Phase I Report, December 2009***

Qualification Protocols

No validated lead-free electronics qualification methods

- **Qualification is used to compare to previous design or material**
  - Just as good, or good enough **in terms of robustness or life in service**
  - Decades of experience and reproducibility of SnPb properties

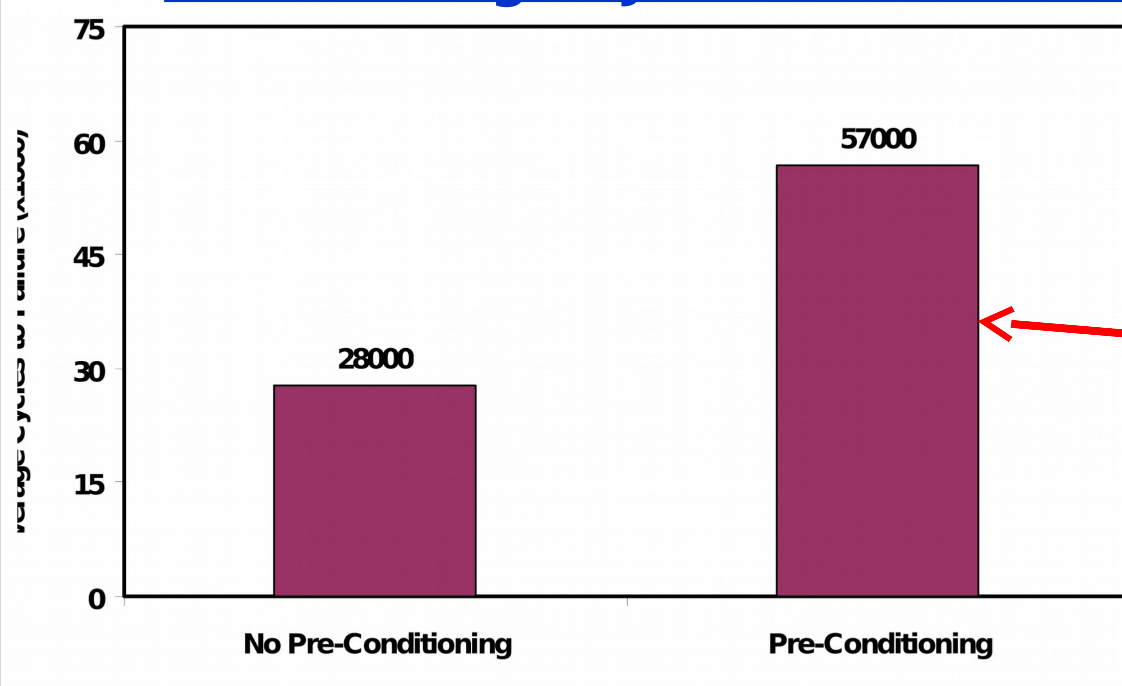
Using existing SnPb electronics qualification protocols for Pb-free electronics will yield erroneous reliability and service life predictions

- **Qualification for Pb-free should consider:**
  - Joint composed of 1-3 Sn grains: **extreme anisotropy** results in strength and failure distribution outliers **unlikely to be captured** by current empirical sampling
  - Comparison of alloys and processes varies with thermal cycling conditions

Qualification Protocols (Cont'd)

- **PCB robustness qualification of new lead-free compatible laminates should consider:**
  - Temperature, aging and humidity changing properties
  - Latent failure risk of repairs
- Realistic **service** environments all involve **combinations of loading**, and **damage doesn't add up** (commonly much greater or smaller than predicted)

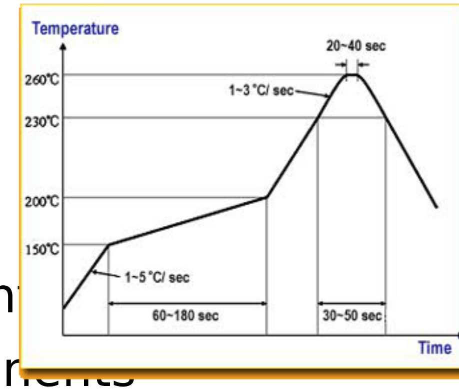
Life of SnAgCu Joints in Vibration



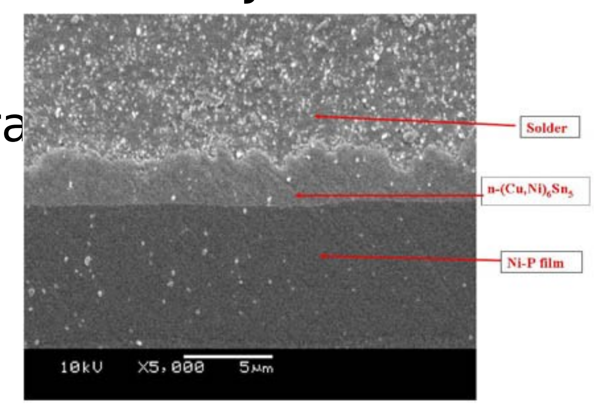
Joints lasted ***longer*** if first exposed to milder cycling!

Components

- **Component Characterization**
  - Temperature exposure limits
  - Moisture sensitivity level
  - Receiving/incoming inspection requirements
  - Storage requirements for unassembled componen
  - Fluxes/cleaning process compatibility with compon
  - Temperature Sensitivity Capability Improvement



- **Component Finish**
  - Re-finishing impact from lead-free to tin-lead
  - Lead-free Finish Effect on Solder Joint
  - Solderability
  - Flux and cleaning chara
  - Corrosion Factors



Pb-free Electronics Risk Reduction Approach Discussion…

Pb-free Electronics Risk Reduction Approach Discussion…

Pb-free Electronics Risk Reduction "Manhattan Project" Concept

- **Who:**
  - The nationally recognized 10-15 deep subject matter experts assembled to work as a single, fully-funded team
  - Strong team leader with requisite management and technical skills
  - Government Funding Champion at highest possible level
- **What:** "Find acceptable replacements for Pb in electronics for use in aerospace and defense environments" (Dual Use)
- **When:** Begin ASAP with a 3-year commitment and hope for shorter
- **Where:** National Lab or Center such as the B2PCOE & EMPF as the "Research Center" with access to other facilities as needed
- **How:** $105M Dedicated "Pocket change funding" compared to the scope of the problem
- **Why:** Given time, the "Business Case" will become self-

Project Participants

- **B2P COE Project Management:**
- **Technical Project Leadership:** (Lockheed Martin) & (Boeing) – Self-funded
- **Meeting Moderator:** Howe School of Technology Management, Stevens Institute of Technology
- **SMEs:**
  - (Universal Instruments/Unovis)
  - (Boeing)
  - (Purdue University)
  - (DfR Solutions)
  - (Rockwell Collins)
  - (Honeywell)
  - (AMRDEC)
  - (BAE Systems)
  - (Univ. of Maryland CALCE)
  - (Raytheon)
  - (Raytheon)
  - (Celestica)
  - (ACI)
  - (Sandia National Labs)
  - (NIST)
  - (Boeing)
  - (Lockheed Martin)

Recommended Roadmap for Pb-free Electronics Risk Reduction

- Coordinated approach proposed to achieve technical consensus
  - Individual companies figuring out unique solutions will result in configuration, contractual and logistics nightmares
  - High cost if each individual company “figures this out” on their own
  - DoD readiness and sustainment will be severely impacted by a non-coordinated approach
- 72 integrated project tasks have been defined
  - Organized under five major “project areas”
  - 15 intermediate “project groups”
  - Durations between 6 and 36 months
  - Most projects estimated to require between $500k and $1M
- Projects typically “collaborate” with at least five other concurrent projects
- Systems Integration Team consisting of Subject Matter Experts required for project coordination and execution

Sample Knowledge Gaps

- Tin Whiskers
  - SnPb design rules used by electrical and mechanical designers are insufficient to ensure reliability of products using Pb-free electronics
  - Need to define the voltage and current conditions for whisker-induced electrical shorting
  - No existing mitigation practice is universally implementable and definitively prevents the occurrence of tin whiskers
  - Insufficient information on how and when tin whiskers can impact circuit performance of high frequency RF circuits

Sample R&D Project Area WBS: Tin Whiskers

A Tin Whiskers

AA Tin Whisker Failure Modes

AAA Metal Vapor Arcing

AAB Voltage & Current Conditions for Whisker-induced Electrical Shorting

AAC RF Effects of Tin Whiskers

AAD Detection of Intermittent Tin Whisker Field Failures

AB Tin Whisker Risk Mitigation

ABA Automate Spacing

ABB Design Rules for Tin Whisker Risk Mitigation

ABC Conformal Coating Whisker Mitigation

ABD Test Method for Tin Whisker Risk at the Part Level for A&D Electronics

ABE Test Method for Tin Whisker Risk at the Product Level for A&D Electronics

ABF New Mitigations

AC Tin Whisker Risk Assessment

ACA Techniques & Procedures to Identify Tin Whiskers on Field Returned Hardware

ACB Circuit Analysis Tin Whisker Risk Assessment

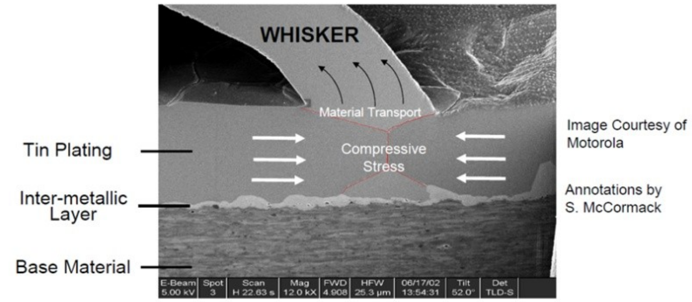
ACC Tin Whisker Life Prediction

ACD Fundamental Research for Tin Whisker Risk Assessment

“Tin Whiskers” Project Area

- **Projects**
  - **Tin Whisker Failure Modes**
  - **Tin Whisker Risk Mitigation**
  - **Tin Whisker Risk Assessment**
- **Outcomes**
  - **Greatly enhanced tools for management of tin-whisker risks**
    - **Provide assurance of long-term system reliability**
    - **Quantify how tin whiskers cause electrical faults**
    - **Determine how to identify these faults**
  - **Mitigations**
    - **New mitigation techniques and mitigation verification tests**
      - **Accelerated quantifiable tin whisker growth**
    - **Integrated design rules**
  - **Life predictions for whisker induced unreliability**
    - **Validated tools for parts and assemblies**
  - **Understanding whisker induced failure modes**
    - **Quantification of circuit shorting or degradation condition**
    - **Detailed functional risk assessments**
  - **Tin whisker field assessment**
    - **Description of the “signatures” of tin whisker induced failure**
    - **Enhancements to data collection protocols**
    - **Increased detection and identification of tin whisker induced problems**
  - **Tin whisker risk assessment processes**
    - **Algorithm development**
    - **Automated circuit analysis**
    - **New whisker inspection techniques**
    - **Fundamental whisker formation kinetics research**

Davy, G., (Northrop Grumman Electronic Systems), “Relay Failure Caused by Tin Whiskers,” http://nepp.nasa.gov/whisker/reference/tech_papers/davy2002-relay-failure-caused-by-tin-whiskers.pdf, June 10,



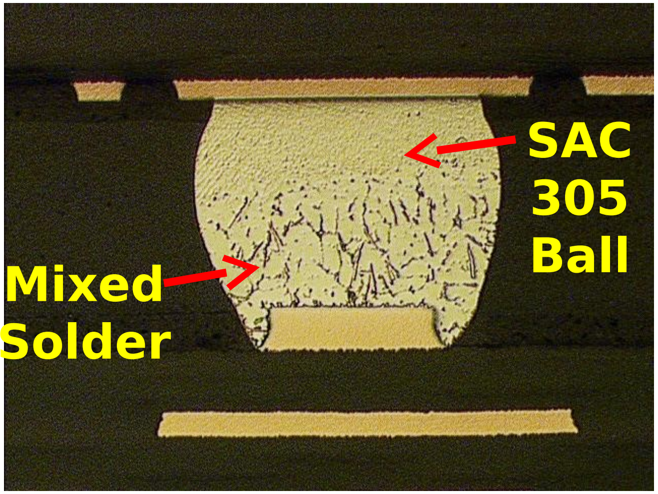
One hypothesis is that whiskers are formed to relieve compressive stress.

Tin Whiskers R&D Schedule

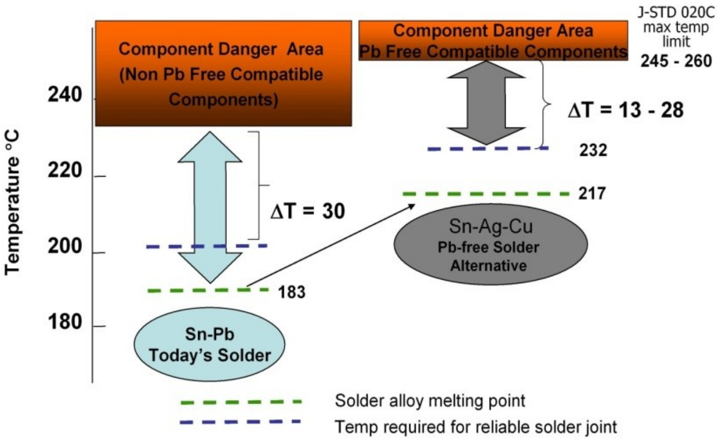
Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Tin whisker failure modes Phase 3 Schedule												
Metal vapor arcing	■	■	■	■								
Shorting and circuit model	■	■	■	■	■							
RF effects	■	■	■	■								
Field detection protocols							■	■	■	■	■	
Tin whisker risk mitigation Phase 3 Schedule												
Design Rules for Tin Whisker Risk Mitigation			■	■	■							
Conformal Coating Whisker Mitigation	■	■	■	■	■	■	■	■				
Test Method for Risks at the Part Level	■	■	■	■	■	■	■	■	■	■	■	■
Test Method for Risks at the Product Level	■	■	■	■	■	■	■	■	■	■	■	■
New Mitigations	■	■	■	■	■	■	■	■	■	■	■	■
Tin whisker risk assessment Phase 3 Schedule												
Tin whiskers on field returned hardware	■	■	■									
Circuit Analysis Tin Whisker Risk Assessment				■	■	■	■	■	■	■		
Tin Whisker Life Prediction months			■	■	■	■	■	■				
Fundamental Research for Tin Whisker Risk Assessment	■	■	■	■	■	■	■	■	■	■	■	■

“Assembly” Project Area

- **Projects**
  - Aerospace and defense (A&D) manufacturing processes
  - Development and validation of qualification and acceptance tests for Pb-Free products
  - Pb-Free pathfinder equipment field assessment
- **Outcomes**
  - Defined set of Pb-free process guidelines for A&D manufacturing
  - Guidelines for rework/repair of A&D assemblies
  - Recommendations on possible non-solder attachment technologies and alternative printed circuit assembly attachment technologies
  - Cost decision matrix comparing relative cost of a current tin/lead solder process versus a proposed Pb-free solder process
  - Qualification and acceptance test parameters based on field life data
  - Field performance data for Pb-free assembly



Complex structure when SAC and SnPb alloys are mixed



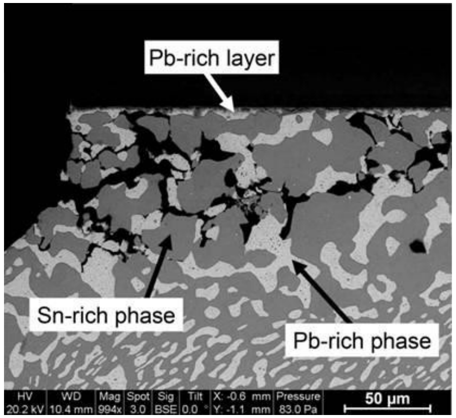
Pb-free process temperature is higher and has challenged the integrity of the polymers and laminates

Assembly (Manufacturing & Repair) R&D Schedule

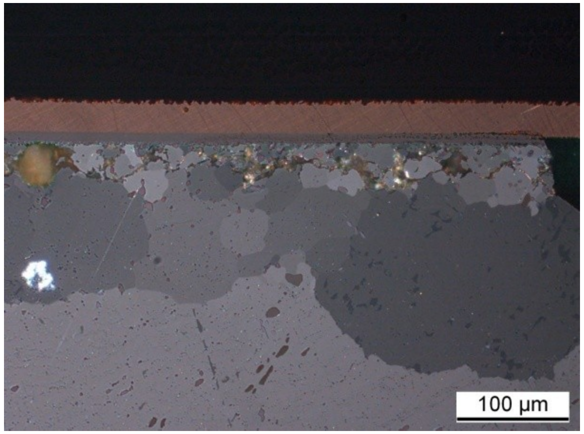
Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Define the critical Pb-free process parameters												
Evaluate/assess the rework/repair of A&D assemblies												
Conduct a "State of the Art" technology assessment – nonsolder attachment												
Method for Determining Qualification and Acceptance Test Parameters												
Field Life Data for Validating Qualification and Acceptance Test Predictions												
Fabrication of ten (10) prototype units												
Assessment of Fielded Pb-free Products												

“Solder Joints” Project Area

- **Projects**
  - Solder Joint Reliability Models
  - Effects Issue Resolution
  - Underfill, Staking, and Coating Models
  - Solder Selection Guidelines
  - Insertion Mount Issue Resolution
  - Handling Guidelines
- **Outcomes**
  - Qualified set of materials for use in A&D applications
  - Models for assessing life and reduction in life due to exposure to environmental stress screens
  - Solder qualification requirements
  - A consistent set of models and data for assessing life expectancy of qualified set of solder materials.
  - Order of magnitude ranking for influences of
    - Electromigration
    - Corrosion
    - Board Finish/Multiple reflows
    - Tin pest
  - Solder acceptance screening requirements
  - Insertion mount fill requirements and rework limits



Sn37Pb Grains coarsen then crack



SAC Grains become finer then crack

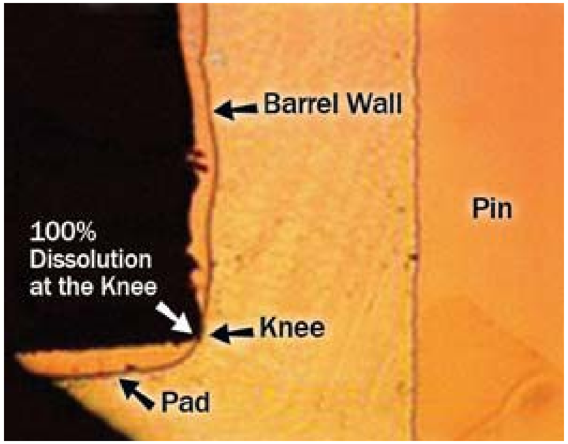
*Images courtesy of CALCE, University of Maryland

Solder Joint Reliability R&D Schedule

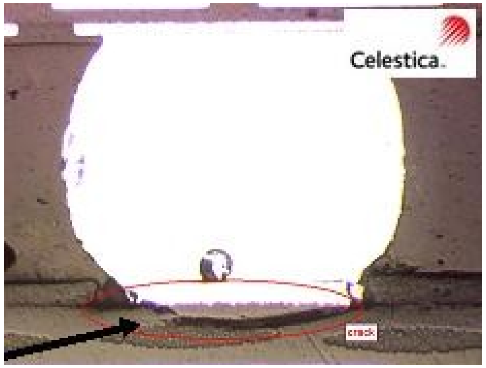
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Solder Reliability Models												
Test vehicles and data collection												
Material Testing												
Reliability Testing												
Model Development												
Optimized qualification process												
Effects Issue Resolution												
Electromigraion												
Corrosion												
Finish/Repair												
Tin Pest												
Underfill Models												
Testing												
Model and Verification												
Solder Selection Criteria												
Insertion Mount Issue Resolution												
Handling Guidelines												

“Printed Circuit Boards” Project Area

- **Projects:**
  - Printed Circuit Board Copper Structures
  - Printed Circuit Board Laminate Materials
  - Printed Circuit Board Surface Finishes
  - Printed Circuit Board Database and Design Rules
- **Outcomes**
  - Validated surface mount pad geometry and stencil design
  - Solder process parameter requirements (reflow, wave, and rework)
    - Control copper dissolution and integrity of copper structures
    - Test methods for void formation at copper/solder interfaces
  - Design rules, procurement specifications, and test method development to minimize
    - Thermal laminate degradation
    - Pad cratering
    - Conductive anodic filament (CAF) formation
  - Laminate capabilities and limitation evaluation
    - Assessment of polymer formulation, glass treatments, glass weave, fillers, and post treatments
  - Quantify finish attributes during initial receipt and after assembly:
    - Robustness in harsh environments
    - Solderability after aging;
    - Corrosion resistance
    - Resistance to forming tin whiskers
  - Evaluate methods for the verification of PCB finishes
    - Initial receipt and repair to ensure that the qualified configuration is maintained.
  - Evaluate suitability of finishes for A&D harsh and long service environments requiring long term corrosion



Copper Dissolution of Plated Thru Hole (Courtesy Celestica)



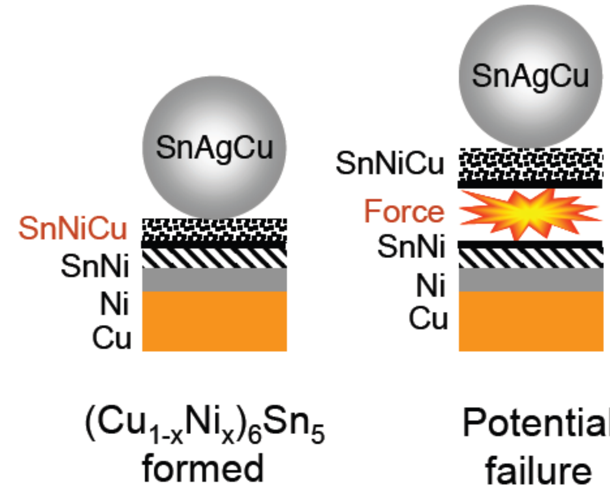
Pad Cratering (Courtesy Celestica)

PCB R&D Schedule

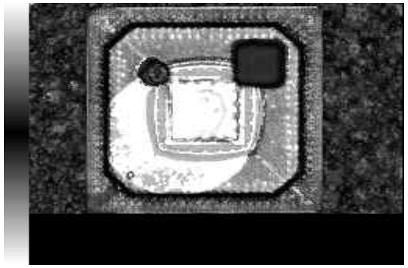
Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Pad Design/Stencil Design Assessment/Confirmation	■	■	■	■								
Copper Plating Requirements & Copper Dissolution					■	■	■	■	■	■		
Void Formation Associated with Solder/Copper Plating					■	■	■					
Thermal Robustness of Laminate Material	■	■	■	■	■	■						
Pad Cratering		■	■	■	■	■	■	■				
Conductive Anodic Filament (CAF)					■	■	■	■	■			
Development of New Laminate Material						■	■	■	■	■	■	
Surface Finish Evaluation	■	■	■	■	■	■	■	■	■	■	■	■
Surface Finish Test Methods	■	■	■	■								
Development of New PCB Plating Material						■	■	■	■	■	■	
Sporadic Brittle Failure of PbFree Solder With Nickel Plating	■	■	■	■	■	■	■	■	■	■	■	■
A&D Laminate Database and Design Rules	■	■	■	■	■	■	■	■	■	■	■	■

"Components" Project Area

- **Projects**
  - **Component Characterization**
  - **Component Refinishing/Reprocessing**
  - **Temperature Sensitivity Capability Improvement**
  - **Component Finish**
  - **Component Corrosion**
- **Outcomes**
  - **Receiving inspection guidelines and incoming requirements for components**
  - **Component properties database for assembly requirements and reliability modeling**
  - **Temperature sensitivity quantification for Pb-free**
  - **Characterization /models of component finish effects on solderability and solder joint reliability**
  - **Methods to assess cost/schedule impact of component refinishing**
  - **Flux and cleaning characteristics**
    - **Determination of flux compatibility with components**
    - **Circuit card assembly cleaning requirements and corrosion/degradation impacts**
  - **Storage requirements for unassembled**



Brittle Sn-Cu-Ni intermetallics can be formed from Cu in SAC solder when soldering to Ni (Gregorich)



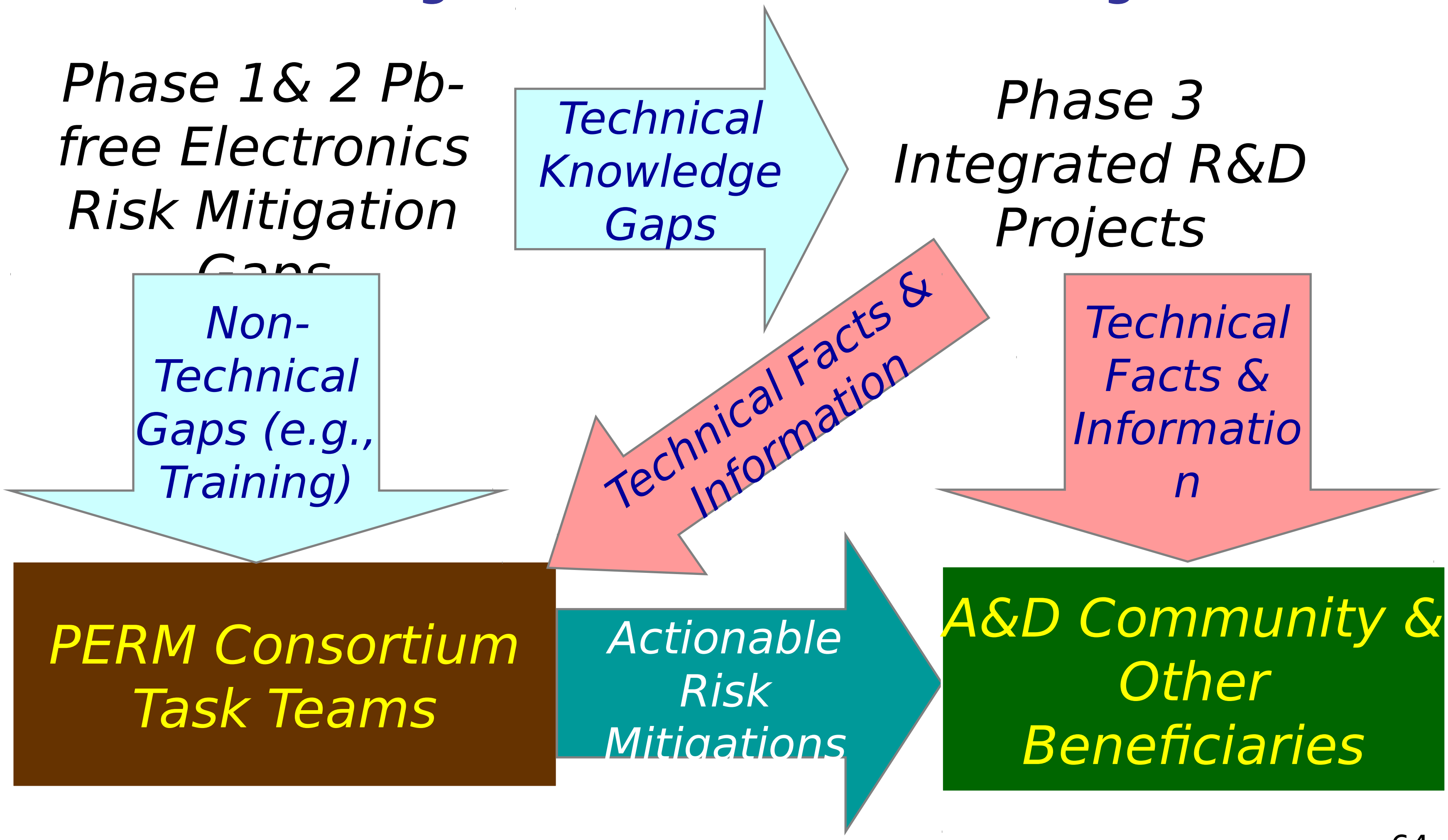
Scanning acoustic microscope image showing delamination (white area) after soldering

Components R&D Schedule

Task	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Temperature exposure limits	■	■	■	■	■	■	■	■				
Receiving/incoming inspection requirements	■	■										
Storage requirements for unassembled components					■	■	■	■				
Component properties database	■	■	■	■	■	■	■	■				
Fluxes/cleaning process compatibility with components			■	■	■	■						
Component Refinishing/Reprocessing					■	■	■	■				
Temperature Sensitivity Capability Improvement					■	■	■	■	■	■	■	■
Finish Solder Joint Effect			■	■	■	■	■	■	■	■	■	■
Solderability	■	■	■	■	■	■						
Corrosion Acceleration Factors					■	■	■	■	■	■	■	■
Corrosion Mitigation							■	■	■	■	■	■

Interface with the PERM Consortium

The PERM Consortium will help convert the R&D findings into Actionable Risk Mitigations



PERM Consortium Membership

PERM Membership

Industry	312
Government	118
Academia	13
International	10
MoD	3
No Affiliation	3
GRAND TOTAL	**459**

Government Membership

- DoD = 99
- NASA = 7
- FAA = 5
- DoE = 4
- NIST = 3